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MedECC Special Report

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Introductory Note

MedECC presently prepares three Special Reports assessing the following issues in the Mediterranean: 1) Climate and environmental coastal risks, 2) Climate-water-energy-food-ecosystems nexus, and 3) Environmental change, conflict, and human migration. These reports will be published between the end of 2023 and the beginning of 2024. In November 2022, the tables of contents of the Special Reports were shared with policymakers and governments, including Plan Bleu Focal Points. The Zero Order Draft of each report underwent the internal review by the authors. The First Order Draft of the report on climate and environmental coastal risks underwent the external review by peer scientific experts (02 May – 17 July 2023), who were invited to comment on the accuracy and completeness of the scientific and technical content and the overall balance of the draft report. In parallel, the draft Summary for Policymakers (SPM) of the MedECC Special Report on climate and environmental coastal risks underwent the external consultation with governments, decision-makers and stakeholders, including UNEP/MAP and Plan Bleu Focal Points (06 June – 17 July 2023). The First Order Draft (FOD) of the full report was also shared as a supporting document. The comments received during the external review will be addressed by the author team to develop the final draft of the report. The revised Summary for Policymakers (SPM) will be submitted to the plenary consultation with policymakers, governments, decision-makers and stakeholders, to take place early November 2023 (online, date tbc).

This present information document contains the FOD of the Special Report on climate and environmental coastal risks. Its SPM is contained in the working document UNEP/MED WG.568/16 Draft Decision 26/13

MedECC Special Assessment Report
Climate and Environmental Coastal Risks in the Mediterranean

Date of First Order Draft: 02 May 2023

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1 Context and framing

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1.0 Executive summary and/or key messages

- A third of the Mediterranean population lives close to the sea and depends on infrastructure developed in the immediate vicinity of the sea. Policies to manage coastal risks and adaptation strategies in the context of sustainable development are important to the whole region. Policy development together with regional cooperation supports greater integration of knowledge, applied to more sustainable and integrated Coastal Zone Management and its proper communication.
- Risk assessments for Mediterranean coastal zones address the specific features of climate, variability and extremes, and the often narrow and over-pressured coastal zones of the Mediterranean Basin. Coastal risk levels, estimated with an explicit treatment of uncertainties can inform adaptation pathways and support coastal sustainability decisions. Coastal hazards, vulnerabilities, and exposure are assessed together with climatic and environmental management scenarios. This combined information provides useful support for a transition towards risk reduction and sustainability in coastal governance, policies and social perception.
- Adaptation pathways provide a sequenced set of interventions to sustain coastal zones and control risk levels, including change stations and tipping points to guide coastal decisions. The preparation of adaptation pathways favours objective discussions among stakeholders to co-decide preferred adaptation options and deadlines for their implementation, which in turn facilitates the generation of sufficient funding and supportive policies
- Coastal risks have consequences for physical locations and social activities. Understanding how risks are distributed within and among communities can inform adaptation policy development. A value-based approach guides the understanding between nature and society, placing the social and cultural values in context within the region.
- Adaptation plans designed by local and regional administrations typically focus on the need to protect communities, and minimise impacts on the natural environment, such as ensuring ecosystem resilience. Including ethical considerations would lead to informed more socially-oriented adaptation policies.

1.1 Introduction

The First Mediterranean Assessment Report (MAR1) on the current conditions and expected risks of climate and environmental change in the Mediterranean Basin was published on 17 November 2020 by the network of Mediterranean Experts on Climate and environmental Change (MedECC) (MedECC 2020). It was prepared by 190 scientists from 25 countries. To produce this report more than 3800 articles and reports in the scientific literature have been assessed. The overarching goal for the development of MAR1 was to cover all major risks associated with environmental change as comprehensively as possible, regarding the major drivers of risk, the major systems impacted and as much as possible the sub regions of the Mediterranean Basin. During this assessment, several important issues have emerged that require deeper analysis, often associated with progress published in new scientific studies. It was therefore proposed that the MedECC community, and the approach developed for MAR1, could be enabled to produce a special report, during the period 2021–2023 addressing coastal risks of the Mediterranean region. The coastal zone is generally defined as the interface between land and sea including the land area affected by marine processes, and the part of the sea affected by terrestrial processes.

The Special Report is structured with an opening introductory chapter (Chapter 1) that provides readers with the context, background and key dimensions, in particular the risk framework, of this assessment. The report has three central chapters: the first that assesses the drivers of coastal risks in the Mediterranean and their interactions (Chapter 2); the second on the coastal climate change and environmental impacts and risks on human and natural systems in the Mediterranean (Chapter 3), and the third on the existing and prospective responses and management approaches to managing climate change and environmental risks, on the existing policy-research interface, and presenting best practices across the Mediterranean region (Chapter 4). The final chapter (Chapter 5) synthesises the available knowledge about climate resilient sustainable development pathways, building on the outcomes of chapters 2 to 4.

This introductory chapter sets the scene for the Special Report in terms of the policy, natural environment and societal context of the report, focusing on the risk framing, as well as key definitions, including context-specific nuances that are relevant across the report. It identifies what is assessed in the report, building on recent developments and considering the latest relevant international assessments. The introduction establishes a common assessment framework to facilitate the communication and synthesis of the results for stakeholders and users more broadly.

1.1.1 Mediterranean coastal risks

A third of the Mediterranean population (around 150 million people) lives close to the sea and depends on infrastructure developed in the immediate vicinity of the sea due to the low amplitude of the tides. 40% of Mediterranean coastal areas are built-up or otherwise modified, often rendering them particularly vulnerable to: a) coastal flooding and erosion, caused by sea level rise in combination with extreme climatic events, and reduced sedimentation in river deltas and estuaries; b) infiltration of seawater into coastal aquifers (seawater intrusion); c) general degradation of coastal habitats, including wetlands, seabed meadows and agricultural systems; d) coastal squeeze and loss of water and sediment quality; and e) cumulative pollution effects at selected sites, whose concentration of human and economic activities has resulting in an increasing degradation of coastal ecosystems.

Mean sea level in the Mediterranean Basin has risen by 1.4 mm yr^{-1} during the 20th century and has accelerated to 2.8 mm yr^{-1} recently (1993–2018). Mediterranean Sea level rise is expected to continue (with regional differences) by the expected global rate of 43–84 cm above current levels until 2100, but with a significant risk to exceed 1 m in the case of further ice-sheet destabilisation in Antarctica (MedECC 2020). Sea level rise will increase most coastal risks through the increase in frequency and intensity of coastal floods and erosion. Until 2100, coastal flood risks, mainly of marine origin but compounded in river mouth areas by combined marine-riverine flooding, may increase by more than 50% and erosion risk by more than 10% across the Mediterranean region (Reimann et al. 2018). Damaging flash floods are likely to increase in many countries including Italy, France and Spain, affecting mainly the coastal areas and river mouth areas, in particular, where population and urban settlements are growing in flood-prone areas, these will likely become more frequent and/or intense due to climate change and surface-sealing. Important challenges to groundwater quality in coastal areas are likely to arise from salt-water intrusion driven by enhanced extraction of coastal groundwater aquifers and sea-level rise.

Reduced precipitation and prolonged droughts will reduce the water discharge and sediment flow of Mediterranean rivers and catchments, leading to the risk of land loss in estuaries and deltas. The agriculture sector will be affected by direct impact on (or loss of) agricultural areas in coastal zones (e.g., in Egypt), along with up to three-fold increases in salinity of irrigation water and soil and retention of sediments that do not reach the coast. Sea level rise affects also coastal wetlands and estuaries with most severe impacts on the less mobile and less resilient species.

Coastal erosion due to sea level rise and urban development will also likely affect tourism. The effect of sea level rise, together with changes in storm features is likely to seriously impact port operations, slowing down trade operations and productivity levels. Parts of the rich Mediterranean cultural heritage, notably many UNESCO World Heritage Sites, are threatened directly by sea-level rise, concentrated precipitation and other aspects of environmental change.

Proactive adaptation to these hazards is essential for maintaining functioning coastal zones. Coastal adaptation practices can be classified in the following broad categories: protect, accommodate, advance, and retreat. Nature-based protection solutions, such as beach and shore nourishment, dune or wetland restoration, reforestation in upstream areas, and adequate agricultural practices to retain water, are becoming a common alternative.

These practices, supported by advanced information such as from Early Warning Systems (EWSs), contribute to reducing flood fatalities and preparing societies to live with natural hazards. The MAR1 report assessed multiple risks faced in the Mediterranean region, defined as a "climate change hotspot" due to the combination of hazards with high exposure and vulnerability. The report will assemble new information and thereby update the assessment of MAR1 about coastal risks, and identify potential for adaptation and risk reduction.

This report will inform Mediterranean policies on the development of an overarching framework to address the United Nations Sustainable Development Goals (SDGs) of particular importance to the whole Mediterranean Region such as combating climate change, increasing food security, managing natural resources, reforming health systems, creating opportunities for social inclusion, economic prosperity, and human equality or reducing risks for geopolitical instability. A science-policy dialogue can support this framing together with a multi-stakeholder approach, strengthened research cooperation mechanisms, and institutional partnerships, together in a shared ownership approach for the benefit of our Mediterranean (Mare Nostrum). Recognizing the value of countries' specificities as a strength for the region, there is the opportunity for a cultural transformation to create a proud community sharing the Mediterranean Sea as a common value.

1.1.2 The science-policy context

The Mediterranean has seen the development of various initiatives and activities that seek to impact policy making by introducing a more systematic approach. Since 1975, Mediterranean countries have established an institutional framework for cooperation in addressing the marine and coastal environmental degradation - Mediterranean Action Plan (MAP), under the auspices of the Regional Seas Programme of the United Nations Environment Programme (UNEP). In 1976, in Barcelona, a framework convention dedicated to the Protection of the Mediterranean Sea Against Pollution was adopted. (Barcelona Convention). Other initiatives followed, such as the BLUEMED initiative and its Strategic Research and Innovation Agenda (SRIA); the EU COST Action on "Ocean Governance for Sustainability"; the EU COST Action for advancing knowledge and unifying concepts and approaches in the emerging field of Marine Functional Connectivity (Sea-Unicorn); the UN decade of ocean science for sustainable development and various training on science-society-policy interface in the Mediterranean promoted by UNESCO, the Union for the Mediterranean (UfM) and other actors; etc. At national level various Mediterranean countries are implementing national level adaptation plans, such as for instance Spain with the PIMA Adapta Costa or Adaptation plans for Harbour Authorities. All these policy developments and regional cooperation initiatives urge for greater integration of knowledge, applied to a more sustainable and integrated Coastal Zone Managements and its proper communication. Thus, the proposed thrust to support a new generation of policy makers through dedicated capacity building, timely science advice to policy and fostering the dialogue within the knowledge triangle (academia-society-policy).

The UfM's policy dimension is structured around regional dialogue platforms involving representatives from governmental institutions and experts, regional and international organizations, local authorities, civil society, private sector and financial institutions. The UfM is also advancing regional and sub-regional cooperation by supporting integration and partnerships within shared objectives, including strengthening cooperation on blue economy and maritime governance and facilitating the transition to sustainable blue economy.

In 2008, fifteen Mediterranean countries signed the 7th Protocol of the Barcelona Convention, Protocol on Integrated Coastal Zone Management for the Mediterranean. The countries have been negotiating for 6 years the text of this Protocol, which is still today innovative in many aspects. Its flagship article, article 8, is the first international legal instrument that lays down the requirement for use of coastal setback zones, a buffer area where certain or all types of development are prohibited or significantly restricted. It identifies a setback zone of a minimum 100 m width from the shoreline as an agreed measure to protect coastal settlements and infrastructure from negative impacts of coastal processes including in particular climate change consequences. Today, this protocol is ratified by 12 Mediterranean countries and the EU.

The MedECC was launched in 2015 with the objective to assess the available scientific knowledge on climate and environmental change and associated risks in the Mediterranean Basin in order to render it accessible to policymakers, stakeholders and citizens. Interactions between MedECC and decision-makers and stakeholders are developed through a science-policy interface built mainly on a close collaboration with Plan Bleu – Regional Activity Center of the United Nations Environment Programme (UNEP) Mediterranean Action Plan (MAP) and the Union for the Mediterranean (UfM).

The MAR1 (MedECC 2020) was an important step to further develop the science-policy dialogue in the Mediterranean. During the 2nd UfM Ministerial Meeting on Environment and Climate Action held in October 2021 in Cairo (Egypt), the 42 Ministers recognized in their declaration the Summary for Policymakers (SPM) of MAR1 as an important contribution of the scientific community to future actions in matters of climate and environment in the Mediterranean region. During the 22nd meeting of the Contracting Parties to the Barcelona Convention COP 22 (December 2021, Antalya, Türkiye), the SPM was endorsed by the Contracting Parties and reflected in the Antalya Ministerial Declaration.

1.1.3 The Mediterranean coastal region

The land-sea coastal border has been defined using objective and subjective criteria, many times with a high level of uncertainty or fuzziness. Depending on the technical, economic or legal implications (e.g., public domain coastal zone) the extent of the coastal border may vary significantly and the variation of these borders with time (e.g., with sea level rise or with background erosion) is seldom explicitly considered in coastal management.

Both the land boundary and the sea boundary of this coastal zone are normally associated with gradients, illustrated by the urbanisation or geomorphological characteristics of the coastal land zone or by the dominance of nearshore and wave breaking processes for the ocean coastal zone. With the advent of new satellite data, providing spatially structured information, new definitions have started to appear such as the characterization of the coastal zone sea boundary in terms of geostatistical anisotropy (Sánchez-Arcilla et al. 2019). These definitions contrast with approaches for the land coastal zone, which define the coastal boundary in terms of elevation or width (e.g., coastal zone as a low elevation swathe).

In the Mediterranean, the land boundary can be often defined by mountain chains (land border) and narrow continental shelves (sea border), leading to different coastal zones depending on the application purpose. From a risk assessment standpoint, the land and sea coastal zones should be considered as a single system, where the land and water parts interact at different scales. In summary, coastal zones for risk assessments should:

- Explicitly define land, sea and lateral boundaries, considering the national legislation applicable
- Address how these boundaries vary with time-scale, considering the continuous land shifting of the public domain land-sea border due to sea level rise compounded by subsidence
- Discuss the uncertainty in defining those boundaries, notably due to meteo-oceanographic variability and the difficulties to establish a rigid delineation for a naturally dynamic boundary

The following is a high-level summary of the aspects of the Mediterranean coastal system assessed, including cross-references to chapters, in the report:

The Mediterranean coastal zone is characterised by a high exposure to erosion and flooding due to cities and infrastructure being built close to the shoreline, within one of the most vulnerable regions to climate change (MedECC 2020). Such closeness and the features of Mediterranean weather, associated with micro tidal ranges, flash floods and limited wave energy (Chapter2), also increase coastal pollution and environmental degradation, which make Mediterranean coasts disproportionately vulnerable to climate change impacts (Chapter 3).

High population pressure and coastal squeeze result in high risks for population, economy and cultural heritage that will increase with sea level rise and increasing temperatures (air and water) due to global warming. This includes negative impacts of population growth, coastal urbanisation, coastal fisheries and agriculture (Chapters 2 and 3).

Weather patterns are highly variable, with rapid storm development, short duration wave storms, medicanes or flash floods. Another Mediterranean specificity are sharp gradients in chemical water properties, illustrated by offshore oligotrophic conditions and with high concentrations of nutrients, plastics and emerging contaminants near the coast due to socioeconomic activities (Chapter 2), particularly near river mouths, coastal cities and port domains (Samper et al. 2022).

Rich coastal geodiversity, with sharp gradients in topography (e.g., mountain chains with river valley openings that condition weather patterns) and bathymetry (e.g., narrow continental shelves with submarine canyons) modulate meteo-oceanographic drivers and affect the impact of geohazards (Chapter 2).

Important differences in institutional capacity, social perception and socioeconomic commitment to sustain coastal zones appear among different Mediterranean countries. In spite of this variety of socioeconomic and institutional conditions (Chapter 4), there is a need for common actions within sustainable adaptation pathways (Chapter 5).

[Start Box 1.1 here]

Box 1.1 Core concepts

Definitions of key terms used in the report (IPCC 2022: Annex II: Glossary)

- **Scenarios** A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

- **Risk** The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems.

In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making.

In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with, or negative side-effects on, other societal objectives, such as the Sustainable Development Goals (SDGs). Risks can arise for example from uncertainty in the implementation, effectiveness or outcomes of climate policy, climate-related investments, technology development or adoption, and system transitions.

- **Adaptation** In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.
- **Adaptation pathways** A series of adaptation choices involving trade-offs between short-term and long-term goals and values. These are processes of deliberation to identify solutions that are meaningful to people in the context of their daily lives and to avoid potential maladaptation
- **Resilience** The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation.
- **Climate resilient development pathways** Trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation to and resilience in a changing climate. They raise the ethics, equity and feasibility aspects of the deep societal transformation needed to drastically reduce emissions to limit global warming (e.g., to well below 2°C) and achieve desirable and livable futures and well-being for all.
- **Governance** The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.
- **Social justice** Just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity and support according to principles of justice and fairness.
- **Climate justice** that links development and human rights to achieve a human-centered approach to addressing climate change, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts equitably and fairly.

- **Equity** The principle of being fair and impartial, and a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. Often aligned with ideas of equality, fairness and justice and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations and gender, and in the sense of who participates and controls the processes of decision-making.

[**Placeholder:** The addition of the figure illustrating the fundamental concept of drivers, risks, vulnerability to climate and environmental change could be added to ease the understanding.]
[End box 1.1 here]

1.2 Climate and environmental change, and impacts in the Mediterranean

This section introduces the Mediterranean coastal zone which is assessed in the report and the climate change and environmental context of the Mediterranean (latest assessment findings of MAR1 (MedECC; 2020), AR6 WGI and WGII (IPCC 2021, 2022)).

1.2.1 Observed and future climate change

The latest Intergovernmental Panel on Climate Change (IPCC) assessment (IPCC 2021) has concluded that human-caused global warming for the period 2010–2019 compared to the period 1850–1900 has reached 1.07ºC (0.8ºC to 1.3ºC *likely* range) and that it is unequivocal that human influence has warmed all parts of the climate system - the land, ocean, and atmosphere. As a result, changes in climate conditions that affect society and ecosystems ("climatic impact-drivers") are occurring in all regions of the world in multiple and concurrent ways and are projected to increase in the future with every increment of global warming. Climate information can contribute to the assessment of future risks and planning for adaptation at regional scales considering the interplay between human-caused climate change, natural variability of the climate system and information on impacts, vulnerability and exposure.

The Mediterranean region has experienced increased mean and extreme temperatures compared to the pre-industrial period that cannot be explained in the absence of human influence. Warming is projected to increase at rates that are greater than the global average, by how much depending on the level of future mitigation of greenhouse gas emissions, as summarised in **Table 1.1**. With every increment of global warming the Mediterranean is expected to experience increased and concurrent climatic impact-drivers, generally hazards (temperature extremes, increase in droughts and aridity, precipitation decrease, increase in fire weather, mean and extreme sea levels, and wind speed decrease) that can lead to impacts on society and ecosystems.

Table 1.1 | Future global surface temperature change for the Mediterranean region. Change in global surface temperature relative to the period 1850–1900 Based on Coupled Model Intercomparison Project Phase 6 (CMIP6) model projections (34 models). Sourced from AR6 WGI Interactive Atlas (Gutiérrez et al. 2021)

Scenario (GHG emissions)	**Near term, 2021–2040**		**Mid-term, 2041–2060**		**Long term, 2081–2100**	
	Median (ºC)	***Very likely* range (ºC)**	**Median (ºC)**	***Very likely* range (ºC)**	**Median (ºC)**	***Very likely* range (ºC)**
SSP1-2.6 (low)	1.8	1.4 to 2.2	2.1	1.6 to 2.7	2.2	1.6 to 3.0
SSP2.4.5 (medium)	1.9	1.5 to 2.3	2.4	1.9 to 3.1	3.3	2.4 to 4.3
SSP3-7.0 (high)	1.8	1.4 to 2.4	2.6	2.0 to 3.3	4.5	3.6 to 5.5

SSP5-8.5 (very high)	1.9	1.6 to 2.5	2.9	2.3 to 3.6	5.5	4.2 to 6.8

1.2.2 Environmental aspects

Most impacts of climate change are exacerbated by other environmental changes, such as land and sea use change (including agricultural intensification, increasing urbanisation and mass tourism, overfishing, land degradation and desertification), pollution (air, land, rivers and ocean) and non-indigenous species (MedECC 2020).

Sea, inland and air pollution in the Mediterranean increases both in quantity and in the number of pollutants. Pollution comes from transport, shipping, unsustainable agricultural, industry and household waste. The Mediterranean Basin is among the regions in the world with the highest concentrations of gaseous air pollutants (NO_2, SO_2 and O_3). Ships and road traffic are the major emitters of SO_2 and NO_x. Emissions of aerosols and particulate matter (PM) into the atmosphere come from anthropogenic activities (transport, industry, biomass burning, etc.), but also from natural sources (volcanic eruptions, sea salt, soil dust suspension, natural forest fires, etc.). Air pollution levels are enhanced by specific atmospheric circulation patterns and by dry and sunny climate (Schembari et al. 2012; Karanasiou et al. 2014; Dayan et al. 2017). Particular meteorological conditions and the proximity of the Sahara Desert influence particulate matter (PM) concentrations, including occurrence of critically high PM concentrations associated with dust outbreaks, particularly in the southern Mediterranean (Ganor et al. 2020).

Mediterranean coasts are polluted due to coastal squeeze, intense industrialization, uncontrolled discharges of municipal and industrial wastewater, riverine inputs and low seawater circulation. The Mediterranean Sea is heavily polluted by plastics, as 730 tonnes of plastic waste enters it daily. Plastic waste represents 95 to 100% of marine floating waste and 50% of litter on seabeds. Plastic could outweigh fish stocks in the near future (in tonnage). There are many coastal uncontrolled landfill sites, particularly on eastern and southern shores (reviewed in UNEP/MAP and Plan Bleu, 2020). The increasing frequency flash floods in the North of the Mediterranean increases the supply of faecal bacteria, viruses and other contaminants to the coastal zone (Chu et al. 2011). In coastal zones eutrophication caused by nutrient enrichment may provoke harmful and toxic algal blooms. These blooms may have negative economic impacts on fisheries, aquaculture and tourism, as well as on human health, as 40% of blooming microalgae are able to produce toxins responsible for different human intoxications. Also emerging contaminants (related recently discovered chemicals or materials) may be harmful to people causing disorders of nervous, hormonal and reproductive system (MedECC 2020).

Mediterranean coastal zones and their ecosystems are also impacted by non-indigenous species. Their number and spread will likely increase in the future and they may sometimes lead to decrease or collapse in populations of native species (Corrales et al. 2018). Most marine non-indigenous species arrive from the Red Sea and Atlantic Ocean, but the highest impact is attributed to those introduced by ships and aquaculture (Katsanevakis et al. 2016). Among known marine non-indigenous species introduced over the last 30 years, invertebrates dominate with >58% (mostly mollusks and decapods), primary producers follow with approximately 23% and vertebrates with 18% (mostly fish) (Zenetos, 2019).

Changes in the use of land and the sea are multiple and have important impacts on coastal zones. Among them urbanisation is a major driving force of biodiversity loss and biological homogenization causing landscape fragmentation (Grimm et al. 2008; Underwood et al. 2009).

Forest and shrub encroachment tend to increase in the North, as a consequence of abandoned agro-pastoralism (Lasanta et al. 2017; Abadie et al. 2018), whereas in many regions of North Africa and the Middle East (but also on some Mediterranean islands), the dominant land use change processes are forest degradation and ecosystem fragmentation, caused by intensified agriculture, overgrazing and overexploitation of firewood (Hansen MC and DeFries 2004).

Marine resource overexploitation and unsustainable fishing practices provoke marine species population decline. Fishing efforts in the Mediterranean have increased over long periods, but particularly so since the 1990's due to new technologies and higher capacity vessels (Colloca et al. 2017). In 2010, the cumulative percentage of collapsed and overexploited stocks exceeded 60% across the Mediterranean Sea, with the eastern Mediterranean being the most overexploited sub-basin (Tsikliras et al. 2013; Tsikliras et al. 2015).

Climate and environmental changes have become major threats to both ecosystems and human well-being in the Mediterranean and their impact is aggravated by ongoing socio-economic and demographic trends. Disadvantaged or vulnerable populations, including the elderly, children, pregnant women and people with low income, are particularly impacted.

1.2.3 Vulnerability, exposure and impacts

Based on the data analysis and integrations conducted in the IPCC recent reports (IPCC 2021; Ali et al. 2022) on climate change impacts and vulnerability of Mediterranean countries, almost all Mediterranean countries are vulnerable to several climate warming impacts, however there are some local variations, in exposure and frequency level according to the specific local and indigenous knowledge of each country, having southern and eastern countries more vulnerable. For example, the North African countries are highly vulnerable to water stress/water scarcity in response to the growing demand for agriculture and irrigation requirements (e.g., Fader et al. 2016; World Bank 2018). Some countries (e.g., Egypt, Spain and Greece) are suffering from salinization of fresh water resources following sea level rise increase and salt intrusions (Ali and El-Magd 2016; Wassef and Schüttrumpf 2016; Sebri 2017; Twining-Ward et al. 2018; Vargas and Paneque 2019).

Most socio-economic sectors in the Mediterranean region are at growing risk with agriculture followed by tourism being most vulnerable (Kallis, 2008; Kutiel 2019), in addition to high vulnerability of North Africa as classified in the Mountains' Atlas (ESCWA 2017). This is greatly impacting both national and regional GDP (Gross Domestic Product), particularly in low-income countries, with expected loss range of 10–13% (in Middle East and North Africa, MENA, countries by 2100) and 0.1–0.4% (in southern Europe by 2080s) with 4.80°C and 20°C increase in global temperature, respectively (Kompas et al. 2018; Szewczyk et al. 2018). Climate change would increase the vulnerability of MENA countries to food production at the local level as well as elsewhere (e.g., China and Russia) due to their high dependence on food importing (Waha et al. 2017). Exporting countries in the Mediterranean region (e.g., France, Italy and Morocco) also affect global food security through increasing product prices and decreasing their availability, quality and quantity. Fisheries of the Mediterranean Sea, which economically accounts for >3.4 billion USD (Randone et al. 2017), are also at greater risk of increased sea temperature with some locations more sensitive (Turan et al. 2016; Ding et. al. 2017; Hidalgo et al. 2018) and others are less vulnerable (northern countries). Mediterranean forests, which are socially and ecologically important and contribute to several ecosystem services, are significantly vulnerable, particularly countries in the northern and southwestern region (Ager et al. 2014; Gomes da Costa et al. 2020). In addition to growing risks of coastal fires, climate change is causing dangerous increase in pest populations, such is for example sharp increase in the Mediterranean bark beetle (Orthotomicus erosus) population size in Croatia (Lieutier and Paine 2016, Pernek et al. 2019).

Having the region's tourism is third globally (Tovar-Sanchez et al. 2019), it is worth mentioning that both coastal and marine tourism industries along Mediterranean countries are vulnerable to climate change (Dogru et al. 2016; Dogru et al. 2019). The economic value of this important sector, which generates annually from 100 billion USD (from marine activities) to 300 billion USD (from coastal activities), will be seriously impacted (Radhouane 2013; Randone et al. 2017). Impacts on maritime transport and trade industry in the region with approximately 600 ports would also have consequences on their share to the GDP of about 20–40% of the regional GDP (Manoli 2021). Human health is significantly vulnerable to climate change (Negev et al. 2015) and populations along the Mediterranean coastal areas are highly susceptible to several climate related events, such as heat waves (Paz et. al. 2016; Scortichini et al. 2018; Rohat et al. 2019), particularly for sensitive population groups (e.g., poor, ill, elderly, obese, children and women) (Linares et al. 2015; Paravantis et al. 2017).

1.3 Coastal risks and adaptation in the Mediterranean

1.3.1 The risk framing of the report

Risk is usually estimated as the product of a hazard, times exposure and times the consequences of that hazard. As a product of probabilities times damages, both referred to a selected spatial domain and for the time scale of the analysis, it is commonly expressed in a monetary unit (€, $, etc.). Such an apparently simple concept however presents multiple difficulties, some of them due to inconsistent language and others due to inherent uncertainties, particularly under future scenarios. These difficulties have hindered a wider and harmonised uptake of risk applications for decision– and policy– making.

One of the main requirements to enable a comparison of risks for different coastal systems is the explicit definition of the spatial domain and time scale for which risks will be assessed, since the results will vary accordingly and will reflect different risk initiation and propagation mechanisms. The selections of temporal and spatial domains, together with the risk dimensions considered, will bound the multi-risk assessments nowadays required in many coastal assessments. The dimensions should consider which drivers (e.g., only sea level, sea-level plus waves, etc.) which responses (e.g., only erosion, erosion plus flooding, etc.) and which interactions (e.g., marine, riverine, and pluvial flooding combined, response with/out rigid infrastructures, response with/out ecosystem services, etc.). The selection of risk scales and dimensions should consider the aims of each application and the level of information available, particularly regarding future downscaled climatic scenarios.

Regarding the spatial domain, coastal risks can be referred to the whole coastal zone for an integrated assessment or to a more constrained sector or component, well-defined and whose interactions with the rest of the coastal system are well established. The difficulties to define the land limit of the coastal zone illustrate the need for clear criteria, since it will critically influence any risk estimation. For instance, risk will be very different if the coastal zone limit is the first line of infrastructure, the landward limit of coastal cities or the whole catchment basin that feeds that coast.

Regarding the time domain, coastal risks should be referred to the horizon or interval for which the risk is estimated, again well-defined according to the aims of each specific project. In common practice risk estimates for the operational conditions of a coastal system may refer to some energetic but not exceptional storm, while risk estimates for survival conditions of a critical coastal infrastructure must be referred to exceptional storms. The same applies to risk assessments under frequent accidents or under exceptional events, which normally result in cascading risks that must also be considered in the analysis, leading to markedly different risk levels.

In addition to the domain and scales for risk estimation, practical applications and scientific analyses will benefit from an explicit list of the key risk variables, if possible ranking them for the assessed risks. We suggest to list the main controlling variables for the various risk assessments in the chapters, defining them in unambiguous terms for specialists and stakeholders alike and distinguishing between: a) biophysical variables (such as sea level rise rate, peak significant wave height and for which return period, some maximum storm surge level, safe pollutant conservations for bathing, acceptable peak water temperatures and nutrient concentrations for aquaculture, etc.) and b) socio-economic variables (population density and total population, some characteristic average income, some measure of infrastructure density and built up density, distance to an average shoreline,etc.).

1.3.2 Adaptation practices

[Placeholder: Introduction to adaptation practices in the Mediterranean.]

The risk reduction measures briefly summarized in *Section 1.3.2* need a temporal and spatial planning to enhance synergies (e.g., compatibility between short- and long-term interventions) and avoid undesired tradeoffs or unacceptable risk levels (e.g., losing unique habitats or irreversible biodiversity degradation). Here adaptation pathways, understood as a sequenced combination of risk reduction interventions, offer an efficient approach to define possible alternatives (pathways), establish deadlines for those interventions (tipping points) and suggest times to consider switching from one pathway to another (changing stations). Delineating such adaptation pathways may favour the inclusion of nature-based solutions in coastal protection plans (Sánchez-Arcilla et al 2022), while facilitating the convergence of stakeholders and scientists into a more systemic approach for coastal sustainability under climate change.

1.4 A guide to the assessment

1.4.1 Common dimensions of integration

The MedECC assessments, as with other international and national assessment processes, is based on the available, relevant evidence in the published literature. This includes different lines of evidence such as observational products, model-based findings and other information based on different types of data and analyses. However, to aid the communication of the report findings, in particular for the preparation of figures and to formulate executive summary statements of the assessment, a common set of key dimensions can be used across the chapters. These dimensions are defined time frames, common baseline for past changes and conditions, a subset of representative scenarios of future changes, and also the use of well-known frameworks, such as the SDGs.

Time frames

Three common time frames have been adopted by the IPCC Sixth Assessment Report to report key findings in time frames that are relevant for policymakers: near-term - the period from 2020–2040 in the context of the timelines for current national emissions reduction pledges as part of the implementation of the Paris Agreement, and the implementation of the SDGs; the mid-term - the period by 2041–2060, the mid-century time frame relevant in the context of infrastructure planning; and the long-term - the possible outcomes by 2080–2100 and beyond the end of the 21st century.

Baseline period

Changes in the climate and in social and natural systems are compared to conditions that existed prior to the advent of rapid industrialisation in terms of fossil-fuel consumption and land-use changes. The period 1850–1900 has been assessed to be suitable as a proxy for pre-industrial conditions, a baseline against which observed historical changes in the climate system can be compared.

Future scenarios

Possible future scenarios form the basis of modelling and analytical studies to explore how socio-economic conditions, emissions of greenhouse gases, land use, the response of the climate system as well as natural and human systems may change in the 21st century and beyond. The international scientific community has developed different scenario frameworks over time with the aim to produce coordinated simulations across the community where datasets and findings can be compared. The latest generation of scenarios is the Shared Socio-Economic Pathways (SSPs) framework (O'Neill et al. 2014, Riahi et al. 2017).

The experimental design is built around a matrix of simulations that consider different socioeconomic developments and different levels of radiative forcing in the year 2100 levels (IPCC, 2021: Chapter 1, Cross-Chapter Box 1.4). The assessment of future climate change, impacts, vulnerability and adaptation actions can be compared for scenarios with high (SSP3-7.0), based on futures with "no-additional-climate-policy" (in the set of RCPs, the equivalent "no additional-climate-policy" scenario was RCP8.5). The new SSP3-7.0 "no-additional-climate-policy" scenario, with intermediate greenhouse gas emissions (SSP2-4.5), and scenarios with very low and low greenhouse gas emissions (SSP1-1.9 and SSP1-2.6). Scenarios with very high greenhouse gas emissions (SSP5-8.5) have been assessed as being less likely in terms of future outcomes, so are not considered to be "business-as-usual" scenarios any longer, based on today's climate policies, though these scenarios cannot be ruled out altogether and are useful to explore low-likelihood, high-risk outcomes.

Sustainable Development Goals

The United Nations 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) was established (UN DESA 2015) to focus international efforts on the multiple intersectionality between different development objectives, including for climate change, for the pursuit of the seventeen Sustainable development Goals by 2030. The SDGs are used in this report to relate the assessment to different development goals.

1.4.2 Communicating assessment findings consistently

Within the intergovernmental context of the IPCC and MedECC, the assessment of the latest available climate science, environmental, and socio-economic knowledge is solicited by policymakers through a science-policy interface to support the development of evidence-based policy development and communications activities in different sectors and contexts. The use of agreed terms that are calibrated to quantify the strength and quality of the available information distinguishes an assessment from a review of the available scientific and technical literature.

The framework of calibrated terms that communicate either qualitatively or quantitatively the robustness and certainty of assessment findings were adopted transversally by the IPCC since the 5th Assessment Report (AR5). This terminology was agreed as an outcome of a Cross-Working Group Meeting on Consistent Treatment of Uncertainties convened in July 2010 (Mastrandrea et al. 2010) for the consistent treatment of uncertainties in the assessment across all IPCC assessment reports. It builds on previous applications in earlier reports (Moss and Schnieder 2000; Mastrandrea and Mach 2017). Mach et al. (2017) report on the lessons learned of the AR5 and provide further guidance on the systematic use of the calibrated terms, considering challenges in communicating findings where there are considerable uncertainties or considering subjectivity in expert judgement. The transparent use of calibrated terms to build a shared understanding of the assessment outcomes is all the more important when evidence-based policy making is set in the context of multiple influences including different value systems (see discussion in Chen et al. 2021).

The terms are calibrated to have the same meaning for a consistent presentation of the assessment across different chapters of a report, or topics assessed in a report or across different reports, so presenting a consistent and comparable picture on the state of knowledge to policymakers. This is a powerful communication tool that is able to clearly transmit the key assessment findings to policymakers or other users more broadly, overcoming the complexity of the underlying literature, which may be based on different disciplines or methodologies, and in an assessment carried out by a diverse set of experts that will also come from different disciplines, contexts and countries.

The calibrated terms quantify:

- **Confidence:** a qualitative measure of the validity of a finding, based on the type, amount, quality and consistency of evidence and the degree of agreement across different lines of evidence or studies. Levels of confidence can be very low, low, medium, high and very high.
- **Likelihood:** a quantitative measure of uncertainty in a finding, expressed probabilistically. This can be quantified based on statistical analyses, expert judgement by the author team or a formal quantitative survey of expert views (expert elicitation).

Figure 1.1 (Figure 1 in IPCC 2021 Chapter 1 adapted from Mach et al. 2017) illustrates the step-by-step process authors use to evaluate and communicate the state of knowledge in their assessment (Mastrandrea et al. 2010). Authors present evidence/ agreement, confidence, or likelihood terms with assessment conclusions, communicating their expert judgments accordingly. Example conclusions drawn from the report are presented in the box at the bottom of the Figure.

Each chapter subsection presents a traceable account of the assessment, starting with an introduction of the topic, what previous assessments had concluded, then discusses the relevant body of literature, including what methods have been used, the understanding of processes and mechanisms and the relevance of these findings, then concluding in an assessment statement that summarises the state of knowledge on this topic. The terms are attributed to the assessment outcome by the author team following an evaluation of the available evidence. They are agreed through a consensus-building discussion of the evidence, reflecting all expert views that are expressed.

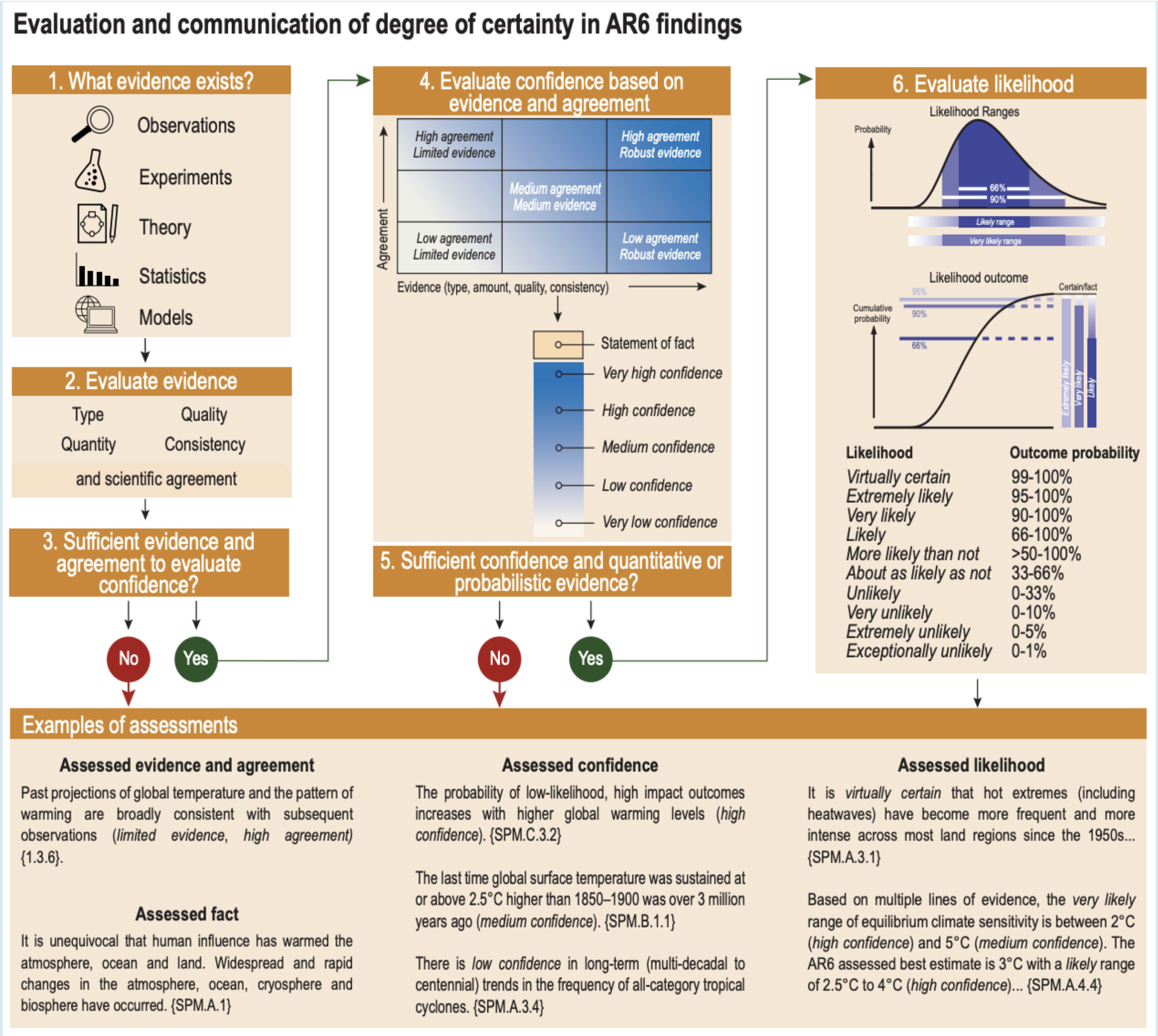

Figure 1.1 | Characterising understanding and uncertainty in assessment findings (IPCC 2021).

1.4.3 Values and the interplay with nature and society

Risk of sea level rise along the coastline impacts physical locations and social activities. To inform adaptation policy, it is necessary to understand how risks are distributed within and among communities. Responding to this need, a value-based approach guides the understanding between nature and society, placing the social and cultural values in the geographic space. The approach explores what people value most about their everyday lives, and how these social values are likely to be affected by environmental changes and the policies developed to respond to such changes (Persson et al. 2015).

Since the Mediterranean coastlines are so densely populated and built up, it is essential to follow a value-based approach to examine the interplay between nature and the potential social impacts of sea-level rise. Some essential social values highly important to residents include scenery, livelihoods and safety. However, local communities have unique social values. Recent studies are facilitating the interplay of social values and with natural risks. There is a large potential to further integrate natural and social approaches to better inform adaptation policy about how lived and landscape values are distributed among communities (Ramm et al. 2017).

1.4.4 Ethical considerations

Some adaptation plans designed by local and regional administrations typically focus on the need to protect communities, and minimise impacts on the natural environment, such as ensuring ecosystem resilience. A notable absence from many plans includes ethical considerations into the assessment process that would lead to informed more socially-oriented adaptation policies.

However, there is a great knowledge gap on the risks and vulnerabilities of many non-material social values. While values-based approaches are receiving increased attention by scholars, it is unclear to what extent they are being adopted by decision-makers (Ramm et al. 2017).

Graham et al. (2014) proposed that values-based approaches could direct policymakers towards ethical considerations in the adaptation process. The approach gives voices to the impacted communities and their social and cultural landscape values, it is inclusive and collaborative and enables decisions to be made that consider diverse values and priorities (Ramm et al. 2017).

The ethical considerations of the assessment process can only be addressed in a systemic approach that includes fairness, resiliency, health, circularity and carbon neutrality. These values establish clear linkages to systemic links to the main elements to be considered in the ethical assessment: societal needs, innovation, behavioural change and long-term visions of society. Clearly, the process is complex, as summarised schematically in **Figure 1.2**, and demands additional resources

Figure 1.2 | A framework for coastal risk management that includes the systemic evaluation of the solutions and the ethical considerations of the assessment process. In the inner circle the attributes of the solutions: resilient, healthy, circular, fair and green. In the outer circle, the ethical considerations: systemic links to societal needs, innovation towards carbon neutrality, changes in behaviour, long term visions and stronger partnerships and timely solutions towards sustainability.

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2 Drivers and their interactions

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2.0 Executive summary and/or key messages

This chapter provides a comprehensive overview of the main natural and socio-economic drivers affecting the Mediterranean coasts. These drivers are of different natures: atmospheric, marine and terrestrial, biological, pollution, and socio-economic. These drivers are responsible for e.g., coastal flooding, marine and coastal use and exploitation, as well as of relevant socio-economic factors, since a large part of the population lives near the coast or exploits marine resources. Some drivers are due to climate change, while others are partially or entirely of anthropogenic origin (e.g., air and water pollution, tourism, urbanization, socio-economic development). The situation can become complex as these drivers occur in temporal sequence, or jointly, or in synergy. This Chapter introduces the drivers, while their impacts will be considered in the next Chapters.

Climate and geological drivers

- As a whole the near surface air temperature of the Mediterranean region at the beginning for the 2020s is 1.5°C warmer than in the preindustrial time (*high confidence*, Section 2.2.1). The evolution of the Mediterranean Sea surface has been characterized by a multidecadal periodicity (~70 years) superimposed to a long-term positive trend of about 0.86°C per century since the preindustrial period (*high confidence*, Section 2.2.1).
- Satellite data show since 1980s spatially inhomogeneous warming rates of the sea surface between +0.29°C and +0.44°C per decade, stronger in the eastern basin, and that over the last two decades mean MHW frequency and duration increased by 40% and 15% (*high confidence*, Section 2.2.5).
- The past changes of sea level have been observed from proxy data over the pre-instrumental period; starting from 1871 with tide gauges; after 1992 with satellite altimetry. The rise rate increases over time, and the longest reconstructed series, for example Venice 7 century long, shows an exponential trend (*observation evidence*, Section 2.2.7).
- On the Mediterranean coasts, referring to the 1850–1900 period, the projected increase of air temperature is 1.6°C to 2.7°C on the mid-term and 1.6°C to 3°C on the long-term for the SSP1-2.6 low emission scenario (*very likely*) and values up to 2.3°C to 3.6°C on the mid-term, and 4.2°C to 6.8°C on the long-term, for the SSP5-8.5 very high emission scenario (*very likely*). (Section 2.2.1)
- The Mediterranean Sea level is projected to rise further during the coming decades and centuries (high confidence), likely reaching 0.28–0.55 m for shared socioeconomic pathways (SSP1-1.9) and 0.63–1.01 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*). (Section 2.2.7)
- The relative sea level rise is increased especially in the areas affected by significant subsidence, such as the coastal region of Thessaloniki in Greece, Mejerda near Tunis, the eastern Nile Delta

in Egypt, the Po Delta and Arno river in Italy. The land subsidence is mainly determined by geological factors but may be increased by human activities. In certain areas it may reach values of the order of 10 mm yr^{-1} or even more (*high confidence*) (Section 2.2.8). The relative sea level is determined by the sum of the local land subsidence and the mean sea level rise presented in Section 2.2.7.

- Coastal flood risks will increase in low-lying areas along 37% of the Mediterranean coastline (*high confidence*) (Section 2.2.4)
- The saltwater intrusion in rivers, estuaries, and coastal aquifers will likely increase, affecting the groundwater resources, the river discharges, the use of the coastal areas, and the most extensive wetlands that are found in relation to the major Mediterranean rivers (*high confidence*). (Section 2.2.4)
- 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 potentially dangerous to people, the environment, and the whole coastal area. In the warm season, increasing aridity or intense precipitation will likely constitute the main challenges (*medium confidence*). (Section 2.2.2)
- A 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 and basin-mean sea surface temperature is expected to increase by 0.6°C–1.3°C before the mid-21st century and by 2.7°C–3.8°C at the end of the 21st century period under the pessimistic RCP8.5 and by 1.1°C–2.1°C for medium, RCP4.5 scenario (high confidence). Not only temperature, but also water salinity and pH acidity will be affected, with likely impacts on the coastal ecosystems on coastal land, or marine. Acidification is projected to continue (*virtually certain*) with a pH decrease of up to –0.46 unit in a high emission scenario. (Section 2.2.5)
- Future reduced precipitation, associated with increased evaporation demand will lead to a decline of runoff in the Mediterranean region and coastal 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*). (Section 2.2.6)

Non-indigenous species

- Warming causes northward migration in the Mediterranean which increases the frequency and the abundance of non-indigenous species, alter seawater quality, biodiversity, food webs and fishery in Mediterranean coasts. The biological invasion through the Red Sea and Atlantic Ocean will be highly dependent on the rate of warming in the Mediterranean. (Section 2.3)

Pollution drivers

- There is robust evidence that the high fluxes of nutrients transported by air, surface water and groundwater to Mediterranean coastal seas 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*). SGD 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*). (Section 2.4.1)
- Concentrations of some pollutants such as lead (Pb) and PCBs will very likely continue to decline in the Mediterranean coasts due to the decrease of dependency and outlawing (*high*

agreement) while some of them, such as antidepressants and plastic, will enhance due to emerging industries, and socioeconomic alteration (*medium agreement*). (Section 2.4)

- Since the Mediterranean Sea is one of the hotspots of non-pollutant drivers such as seawater warming, acidification and deoxygenation, along with the pollutant drivers such as plastics, trace elements, and emerging pollutants, their co-occurrence will likely increase along the Mediterranean coasts. (Section 2.2.5 and 2.4)
- Annual plastic leakage into the Mediterranean coastal area 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. In the scenario of 1% annual growth in plastic production and improved waste management, the leakage is likely to decrease by 2040. (Section 2.4.3).

Social and economic drivers

- Under all socio-economic projections, the total population of the Mediterranean coastal region will continue to grow (*medium confidence*). In the past, the 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*). Egypt, Libya, Morocco, and Tunisia are the coastal regions most exposed to sea level rise due to their large coastal floodplains and significant coastal population growth. (Section 2.5.1).
- The Mediterranean countries have higher urbanization rates than the rest of the world. Currently, two out of three people live in urban regions (*medium confidence*). (Section 2.5.1)
- Climate change, with increasing sea level rise and storm frequency, will negatively impact port structures and operations. (Section 2.5.2)
- Climate change will likely affect coastal sustainable development. On the one hand, energy related infrastructures will become widespread, impacting on land use and pollution levels. On the other hand, the distribution of sediments over the coastal regions will be highly affected by environmental changes. (Section 2.5.2)
- The Mediterranean coast is the world's leading tourism destination and the past projections included a very optimistic development (*high confidence*). However, COVID-19 pandemic and the growing geopolitical conflicts caused a very severe decline (up to 80%) and the whole sector is suffering uncertainties (*low confidence*). (Section 2.5.2)
- With the increasing use of freshwater and the expected increase of aridity, the desalination for drinking water, livestock or agricultural use is important and it is *very likely* that it will continue to gain importance on the coast of Malta, Algeria, Egypt, Israel, Italy and Spain In the Middle East and North Africa. (Section 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 locally 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 some others are expected to become extinct (*very high confidence*). (Section 2.5.2.4).

2.1 Introduction

A driver is any natural or human-induced factor that directly or indirectly causes a change in a system (IPCC 2021: Annex VII: Glossary). Most drivers, especially those related to climate change, pollution, or human activities, have been presented and discussed in IPCC 2021 and 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 are both drivers and consequences of the changes (that is new drivers). The aim is to summarise the key drivers that govern the sea level and the coastal ecosystem of the Mediterranean, and constitute the necessary prerequisite to understand what is explained in the next Chapters. Some of these drivers are altering, or may modify, the sea level, the coast, the coastal ecosystems, the exposure and vulnerability of coastal communities. Recent and historical demographic and settlement trends and anthropogenic subsidence have played an important role in increasing low-lying coastal communities' exposure and vulnerability to sea level rise (SLR) and extreme sea level events.

Although this report is especially concerned on climate change and related potential impacts on the Mediterranean coast, mitigation measures and adaptation, some climate-independent drivers cannot be disregarded because they act in synergism with climate-related effects. For instance, urbanisation, defence plans against coastal submersion and national emergency preparedness are based on the relative sea level, for example the sum of the global sea-level-rise and the local land subsidence. Subsidence increases the frequency and severity of coastal floods. The holistic defence and preparedness against coastal flooding should consider wind waves, storm surges, and tsunamis, as well as their temporary association. Some particular seasons or meteorological situations may generate consecutive storm surges and wave hazards, or their combination, that can lead to amplified flood and erosional damages. This chapter considers a comprehensive frame of drivers relevant for coastal communities, with a special attention to climate change projections and their potential synergism with other natural or anthropic drivers.

The identification of drivers helps to identify critical issues, predict changes and hazards, and assess risks (Chapter 3). On this ground, it will be possible to adopt measures to reduce potential damages or to adapt to climate change in ecosystems and human systems (Chapter 4) as well as to plan sustainable developments (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

Over the past centuries, solar forcing and large volcanic eruptions strongly influenced the temperature variability over the Mediterranean. A combination of climate reconstructions, documentary sources proxies and instrumental data suggests that on the long-term timescale (e.g., since the Roman times and particularly over the last 500 years), the Mediterranean experienced warming-cooling cycles, but the temperature reached in the most recent 3 decades has been unparalleled. As a whole the near surface air temperature of the Mediterranean region at the beginning for the 2020s is 1.5°C warmer than in the preindustrial time (*high confidence*, *Section 2.2.1*). The evolution of the Mediterranean Sea surface has been characterized by a multidecadal periodicity (~70 years) superimposed to a long-term positive trend of about 0.86°C century since the preindustrial period (*high confidence*) (Axaopoulos and Sofianos 2010; Rivetti et al. 2017; Darmaraki et al. 2019; 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–0.5°C per decade (Lionello and Scarascia 2018; Bilbao et al. 2019). All studies, and IPCC 2021 as well, present a strong consensus that present-day warming is robust throughout the Mediterranean region (*high confidence*), although magnitude and level of significance of the observed temperature trends in the Mediterranean coast varies, 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–5.6°C compared to the last two decades of the 20th century, depending on the emission scenario (*high confidence*) (Boberg and Christensen 2012). MedECC 2020 and IPCC 2021 maps show that the most severe warming will likely occur on the mountains and the coasts of the easternmost Mediterranean Sea, for example Syria, Lebanon, Israel and Egypt.

The Mediterranean Basin is among the most responsive regions to global warming (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, 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, Gutierrez et al. (2021) projected a temperature increase of 1.6°C to 2.7°C on the mid-term, and 1.6°C to 3°C on the long-term, for SSP1-2.6 low emission scenario (*very likely*) and values up to 2.3°C to 3.6°C on the mid-term, and 4.2°C to 6.8°C on the long-term, for SSP5-8.5 very high emission scenario (*very likely*).

Projected changes in extreme temperature indicators suggest that the frequency and severity of heat waves will increase (*very high confidence*). Marine heatwaves 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 marine heatwaves by 2081–2100, relative to 1850–1900, by approximately 50 times under RCP8.5 and 20 times under RCP2.6 (*medium confidence*) (IPCC 2021).

Daytime temperatures are expected to increase more than nighttime temperatures, indicating an increase of the amplitude of the diurnal temperature range. The number of warm and tropical nights has also increased over most Mediterranean locations including Iberia, North Africa, Italy, Malta, Greece, Anatolia and the Levant. These parts of the Mediterranean will likely face an increase of more than 60% in the number of tropical nights. The increase of 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 (Lionello and Scarascia 2020). Satellite investigations made on cities located inland and on the coast of the Iberian Peninsula have found no evidence that the effect of urban heat island on the coasts is more enhanced than inland, but that the result may change with the characteristics of the cities, that is the choice of the case studies (Hidalgo Garcia et al. 2022).

2.2.2 Precipitation

The synthesis made by IPCC 2021 is that precipitation will likely decrease in most areas by 4–22%, depending on the emission scenario (*medium confidence*). Rainfall extremes will likely increase in the northern part of the Mediterranean coast (*high confidence*). Droughts will become more prevalent in many areas, especially in the easternmost and southern Mediterranean coasts (*high confidence*) (Ali et al. 2021; UNEP/MAP and Plan Bleu 2020).

The sign of the observed precipitation trends over the Mediterranean exhibits pronounced spatial variability and depends on the time period and season considered. Several studies have assessed changes in interannual variability of precipitation over the Mediterranean region but the magnitude and pattern of precipitation decrease vary widely across models, even with contrasted trends (Peña-Angulo et al. 2020; Vicente-Serrano et al. 2020). Model projections suggest that global warming will further increase the existing difference in intensity of precipitation and hydrological extremes between North and South Mediterranean areas (*high confidence*). The projected increase of dry spell length is larger in the South than in the North Mediterranean (Lionello and Scarascia 2020) *(medium confidence).* Future projections made by Zittis et al. (2021) indicate a strong North/South Mediterranean gradient, with significant, decreasing 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.

Concerning the daily extreme precipitation events on the Mediterranean coast, at the 50-year return level, an Italian station (Genoa) has the highest value of 264 mm, while the other values range from 82 to 200 mm. Furthermore, six series (from stations located in France, Italy, Greece, and Cyprus) show a significant negative tendency in the probability of observing an extreme event (Toreti et al. 2010). The 100-year extremes have no specific trend or preferential areas (Peña-Angulo et al. 2020; Vicente-Serrano et al. 2020). The contribution of the wettest day per year to the annual total precipitation is expected to increase (5–30%) throughout the whole Mediterranean region.

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 northward the mid-latitude westerlies and the storm tracks, 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 the precipitation regime (D'Agostino and Lionello 2020).

Winds

Surface wind speed and its changes on different temporal and spatial scales are governed by driving and drag forces, where all relevant contributions are difficult to estimate and disentangle. In addition, observation-based studies of winds over the Mediterranean are less frequent than for other meteorological variables. The 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. During summer, a possible decline in sea-level pressure over North Africa and the southern Mediterranean is expected. In most regions, wind trends were found non-monotonic over the past decades and concrete conclusions are difficult to be established.

Despite the uncertainties in future projections, there is a general agreement for a limited wind speed reduction over 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 is projected to have small changes and Tramontane a significant decrease in the 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 their speed (Ezber 2018; Belušić Vozila et al. 2019; Dafka et al. 2019).

Cyclones affecting the Mediterranean coasts

The Mediterranean is one of the main cyclogenetic areas of the world, and the most affected areas are the northwestern Mediterranean, North Africa, the north shore of the Levantine Basin (Miglietta 2019). The western Mediterranean is the main cyclogenesis area for both positive and negative anomalies. Atlantic cyclones mainly produce positive sea level anomalies in the western basin. At the easternmost stations, positive anomalies are caused by cyclogenesis in the eastern Mediterranean. North African cyclogenesis is a major source of positive anomalies on the central African coast and negative anomalies on the eastern Mediterranean and northern Aegean coasts (Lionello et al. 2019). A sub-group of hybrid depressions of extratropical cyclogenesis, the so-called Medicanes (Mediterranean hurricanes) or tropical-like cyclones may form in the Mediterranean. During the recent past, there is an absence of strong trends in cyclone numbers affecting the Mediterranean (*medium confidence*).

It has been found that the coasts most exposed to risk for high waves are mainly located in the central and western Mediterranean. Higher frequency and extreme values are present in the Gulf of Lion, affecting the southern coast of France (Patlakas et al. 2020). The significant wave height (H_s) induced by Medicanes along the Mediterranean coasts, and their 100-year return level (RL), have been considered for the present-day. According Toomey et al. (20022), for 71.4% (22.4%) of the continental coastal points, 100-year RL of H_s are greater than 5 m (9 m). These values increase for islands up to 93.2% for 100-year RL larger than 5 m and 30% for 9 m (*medium confidence*). The largest values of the sea surface elevations are found in the coasts of the northern Adriatic Sea (caused by storm surges induced by southeasterly wind setup effect) and in regions with wide shallow continental shelves (Gulfs 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). Although the number of Medicanes has likely decreased, this reduction is not statistically significant (Romera et al. 2017; González-Alemán et al. 2019). The projected changes of Medicane-induced coastal hazards toward the late 21st century show a limited multimodel agreement in terms of magnitude and even sign of the projected changes along most of the coastal regions (*low confidence*) (Toomey et al. 2022).

The origin and track of cyclones producing intense precipitation differ among different areas. For the end of the 21st century, models project a robust decrease of the number and intensity of cyclones crossing the central part of Italy, Tyrrhenian Sea, part of the Anatolian Peninsula, Balkan area and part of Northern Africa and an overall weakening of the systems crossing the Mediterranean region. A robust increase in the cyclone-related precipitation and wind intensity in the central part of the Mediterranean region is also expected. The decrease of the precipitation in the Eastern part of the Mediterranean will be only partially compensated by the increase in the intensity of the rainy events associated with each cyclone (Reale et al. 2022). Conversely, models predict a change of opposite sign in precipitation and wind intensity in the southeastern part of the region. Both signals are spatially coincident with the decrease of the number of tracks 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, but the magnitude of the projected changes varies considerably across models, especially over the Ionian Sea and Iberian Peninsula (Reale et al. 2022) (*medium confidence*).

2.2.4 Storms and (temporary) coastal flooding

Temporarily higher sea levels for inverse barometer effect, storm surges and wind waves may occur separately, or temporarily clustered in particular seasons, or in synergism. Rising mean sea levels driven by climate change and possible changes in storminess (Fox-Kemper et al. 2021) will likely lead to increased clustering of storm surges, waves, and high still sea levels, further exacerbating the impacts of flooding and erosion.

Storm surges

Mediterranean cyclones are responsible for severe storm surges flooding the coastal areas, but the flooding frequency and depth of flooding waters depends on a complex combination of factors including coastal morphology and local sea level. The local sea level is due to the sum of the sea level rise (SLR) and the local land subsidence (LLS), and may be amplified by waves, wind, intense precipitations, currents and other factors. The rise in frequency of concurrent extremes in precipitation and meteorological tide is particularly evident for coasts in northern Mediterranean (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 thermosteric expansion will increase mean sea level. To a large extent, these two effects will compensate for each other, so that their superposition will increase/decrease the maximum water level along two comparable fractions of the coastline (about 15–20%) by the mid 21st century. However, mass addition across the Gibraltar Strait to the Mediterranean Sea will likely become the dominant factor and determine an increase of the maximum water level along most of the coastline (Lionello et al 2017). Analyses of tide gauge data have revealed an increase in the magnitude and duration of the extreme sea level events in the region during the last decades, caused by the rise in the relative mean sea level (Lionello et al. 2021; Zanchettin et al. 2021; Camuffo 2022a, b). 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 inverted barometer effect (D'Agostino et al. 2017, 2020; Grise et al. 2019). The magnitudes of 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, the low-pressure systems are predicted to be the main drivers of high surges, while in the Adriatic Sea the adverse wind conditions (Androulidakis et al. 2015). These predictions have been made omitting the steric effects, tides, sea level rise and the mass inflow of Atlantic waters. In the Mediterranean, higher values are found in the northern Adriatic (between 150 and 200 cm) while in the rest of the domain they vary between 20 and 60 cm (Marcos et al. 2009). The subtraction from the extreme sea levels of the corresponding annual median sea level results in a reduction in the magnitude of trends at most stations, leading to the conclusion that much of the change in the extremes is due to change in the mean values (Menéndez and Woodworth 2010). The future sea level rise will become the dominant factor and it will lead to an increased frequency and intensity level of coastal floods (*very likely*) (Camuffo et al. 2017; Lionello et al. 2017; Vousdoukas et al. 2017; Camuffo 2022a, b). A moderate scenario suggests (*likely*) a 10% and 30% increase in 100-year of extreme sea level in 2050 and 2100, respectively. A high-emission scenario shows a 25% increase already in 2050, reaching 65% in 2100. These ranges are further enlarged by the uncertainty in scenario projections (leading to a 100-year extreme sea level increase of up to 65% and 160% in 2050 and 2100, respectively), which should be further expanded to higher values including high-end scenarios (Lionello et al 2021).

Wind waves

In the Mediterranean Sea, the mean wave heights (1–1.5 m) are lower, and the periods (5–6 s) shorter than in the Atlantic, and present a relevant spatial variability due to the complex orography and coastline surrounding the basin (Menéndez et al. 2014). Since waves are primarily driven by winds, high waves are present over most of the Mediterranean Sea and tend to reach the highest values where strong wind and long fetch are simultaneously present. Wind waves are driven by wind and continue by inertia their motion, until they impact on a coast facing the wind, causing coastal erosion. The highest values (5–6 m) extend from the Gulf of Lion to the southwestern Sardinia through the Balearic Sea and are sustained southwards approaching the Algerian coast (Lionello et al. 2017). They result from northerly winds dominant in the western Mediterranean Sea (Mistral or Tramontana) that become stronger due to orographic effects, and act over a large area, impacting 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 (4–5 m) that will impact on the eastern coasts of Greece and northern Africa. In the Aegean and Levantine Seas, high waves (4–5 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 (Ezber 2018; Obermann-Hellhund et al. 2018; Dafka et al. 2019). Model projections suggest that future changes in waves will be determined by changes in the wind field over the Mediterranean Sea (*very likely*). Published studies point towards a generalised reduction of the mean significant wave height field over a large fraction of the Mediterranean Sea, especially in winter (Hueging et al. 2013; Tobin et al. 2015; Moemken et al. 2018). Similarly, the wave extremes are expected to decrease in number and intensity, although there is no consensus whether very large extreme events, associated with very strong winds, would also decrease *(low confidence)*. A simulation made with an ensemble of 7 models under emission scenario RCP8.5 over 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 (De Leo 2021).

2.2.5 Sea water temperature, salinity and acidification

Sea water temperature

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

Satellite data show since 1980s spatially inhomogeneous warming rates of the sea surface between +0.29°C and +0.44°C per decade, stronger in the eastern basin, and that over the last two decades mean MHW frequency and duration increased by 40% and 15% (*high confidence*) (CEAM 2019, 2021; Darmaraki et al. 2019a; Pisano et al. 2020; Ibrahim et al. 2021). The sea surface warming has not been uniform, but mostly bimodal with stronger trends in the eastern basin (Adriatic, Aegean, Levantine and North-East Ionian Seas), while a spot in the Ionian Sea has warmed 50% less than the basin 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 the last decades (Oliver et al. 2018; Darmaraki et al. 2019a).

Model projections suggest a 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, the sea warming will generally remain below that of the air over surrounding land (*high confidence)* probably causing an increase in land-sea temperature contrast. Compared to the end of the 20th century, the annual-mean and basin-mean sea surface temperature is expected to increase by 0.6°C–1.3°C before the mid-21st century and by 2.7°C–3.8°C at the end of the 21st century period under the pessimistic RCP8.5 and by 1.1°C–2.1°C for medium, RCP4.5 scenario (Darmaraki et al. 2019b). Future warming will be roughly homogeneous in space (*medium confidence)* with the Balearic Sea, the North Ionian Sea, the northeastern 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 *(medium confidence),* resulting in substantial increase in warm extremes and a weaker decrease in cold extremes (Alexander et al. 2018; Darmaraki et al. 2019b; Soto-Navarro et al. 2020).

Salinity

Coastal gradients of soil salinity are established from the seashore to inland areas, and also 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, being average at the rocky coasts and negligible at the sandy shores (Maccioni et al. 2021).

Direct observations and numerical simulations show that the deep Mediterranean waters are becoming saltier. The future evolution of sea surface salinity of the Mediterranean Sea remains largely uncertain as its sign of change. Any change will likely be spatially and temporally inhomogeneous (*medium confidence*) due to the primary role of the river and near-Atlantic freshwater inputs (Soto-Navarro et al. 2020).

Across the Strait of Gibraltar, the 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 (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 to +0.16 psu for the pessimistic RCP8.5 scenario and from –0.25 to 0.25 psu for 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; +0.51 psu) (Soto-Navarro et al. 2020).

Acidification

Excessive nutrient discharges and associated microbial bloom is the main reason 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 units pH_T y^{-1}) in 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 East and South Mediterranean coasts (see *Section 2.4.1*), which will exacerbate the coastal acidification in East and South coasts (*medium confidence*).

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. 0.10-0.15 decrease in pH) since the industrial revolution. Average in situ pH decline is 0.002-unit y^{-1} in world oceans (IPCC 2021), similar to 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) in the North Western Levantine Basin. Since pH trend in offshore and coast are similar in the Mediterranean Sea (Hassoun et al. 2022), acidification is projected to continue both off-shore and coast (*virtually certain*) (Seneviratne et al. 2021; Hassoun et al. 2022). pH will decrease between –0.25 and –0.46 in Mediterranean surface waters by the end of this century compared to pre-industrial era in high CO_2 emission scenarios (*medium confidence*) (Goyet et al. 2016; Hassoun et al. 2022; Reale et al. 2022; Solidoro et al. 2022).

2.2.6 Net hydrological balance: evaporation, precipitation and river runoff

Overall, the net surface water loss over the Mediterranean Sea (evaporation minus precipitation over the sea) has increased over most of the Mediterranean surface, mainly due to a decrease of precipitation during the period 1960–1990 and a 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 2022).

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

Water stress refers to freshwater withdrawals as a proportion of 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*) (Sánchez-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 some decrease of 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; Figure CCP4.3 in 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 (*high confidence*) that future reduced precipitation, associated with increased evaporation demand will lead to a decline of runoff in the Mediterranean region (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) reported a possible runoff decline by 12–15% or more in most locations.

2.2.7 Sea level rise and (permanent) coastal submersion

During the 20th century, coastal tide gauges around the Mediterranean have recorded a rise in the mean sea level. Once tide gauge data have been corrected for the vertical land motion, the sea level trend is very consistent among sites being ~1.4 mm yr^{-1} (Wöppelmann and Marcos 2012). This trend is superimposed on interannual and decadal variability that can temporarily mask the sea level rise. For the more recent period, in which sea level has been monitored by satellite altimetry (1993–2018), the trend of the sea level in the Mediterranean has increased up to 2.8 ± 0.1 mm yr^{-1}, consistent with global sea level trend (3.1 ± 0.4 mm yr^{-1}) (Cazenave and WCRP Global Sea Level Budget Group 2018). In the Northern Adriatic Sea, where there is one among the worldwide longest instrumental time series, obtained combining tide gauge record (1871 to present) with proxies (arriving back to 1350), the sea level has shown an exponential trend **(Figure 2.1, evidence of observed data)** (Camuffo et al. 2017; Camuffo 2021, 2022b).

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 0.28–0.55 m under the very low greenhouse gas (GHG) emissions scenario (SSP1-1.9), 0.32-0.62 m under the low GHG emissions scenario (SSP1-2.6), 0.44–0.76 m under the intermediate GHG emissions scenario (SSP2-4.5), and 0.63–1.01 m under the very high GHG emissions scenario (SSP5-8.5), and by 2150 is 0.37–0.86 m under the very low scenario (SSP1-1.9), 0.46–0.99 m under the low scenario (SSP1-2.6), 0.66–1.33 m under the intermediate scenario (SSP2-4.5), and 0.98–1.88 m under the very high scenario (SSP5-8.5) (*medium confidence*) (IPCC 2021 page 28). On the basis of regional projections of sea-level rise and an understanding of the local and regional processes affecting relative sea-level trends in Venice, the *likely* range of atmospherically corrected relative sea-level rise in Venice by 2100 ranges between 32 and 62 cm above the end of the 20th century level for the RCP2.6 scenario and between 58 and 110 cm for the RCP8.5 scenario (Zanchettin 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).

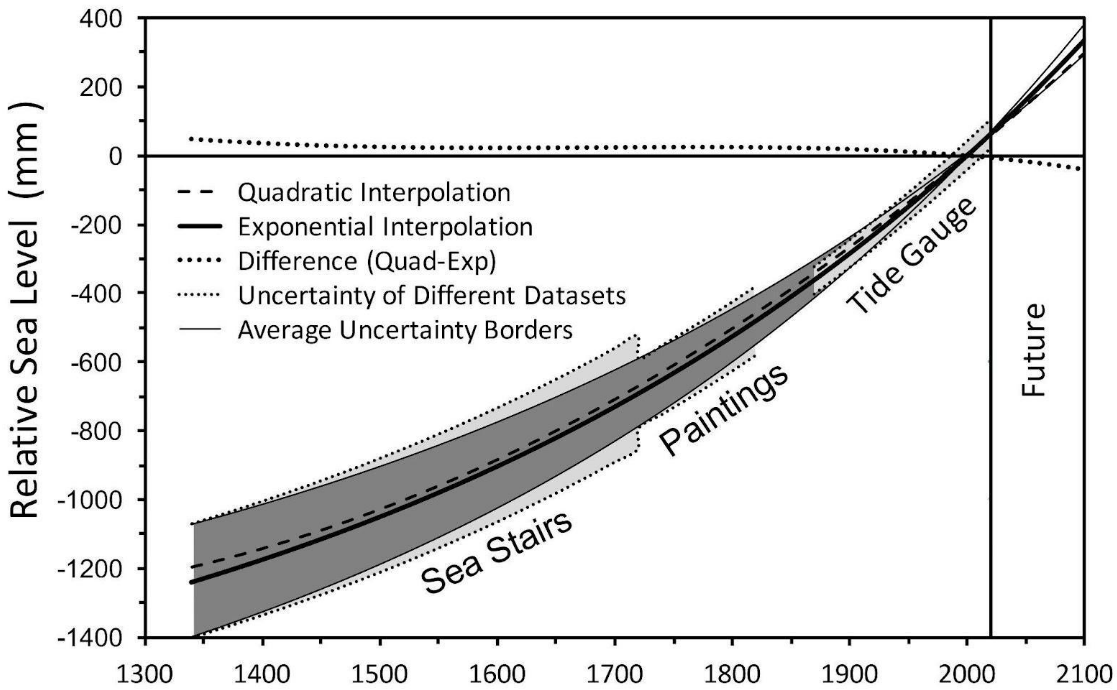

Figure 2.1 | Exponential trend of the Relative sea level rise at Venice observed from tide gauge record (1871–2021), Canaletto, Bellotto and Veronese paintings (18th century and 1571) and submersion of the sea stairs used as a proxy (1350–1750). Uncertainties are specified in the legend. The future is based on the trend extrapolation method, which constitutes the projection of a highly inertial system (Camuffo 2022b).

2.2.8 Natural and anthropic land subsidence over 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 next decades (Nicholls et al. 2021; Spada and Melini, 2022).

In the Mediterranean, coastal subsidence is controlled by negative crustal movements driven by glacio-hydroisostatic 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). The compaction-related subsidence can be substantially enhanced by human activities such as extraction of groundwater, natural gas or oil drilling, have significantly increased the local land subsidence (Tosi et al. 2013; Calabrese et al. 2021).

Negative land-level changes 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) are difficult to model. In fact, these processes can show lots of variability in a relatively small area and data are only available for those sites where geological or geodetical surveys were carried out **(Figure 2.2)**. Combining the projections of the sea level rise with the local land subsidence over the Mediterranean coasts, one obtains the key information concerning the real risk of coastal submersion.

In the southern portion of the Mediterranean Basin, subsidence rates up to ~10 mm yr^{-1} affected the Nile delta (Egypt,) and the Medjerda coastal plain (Tunisia) (Besset et al. 2017; Saleh and Becker, 2018). Lower subsidence rates, ~3 mm yr^{-1}, were observed at the Moulouya river mouth (Morocco) (Besset et al. 2017). Along the northern Mediterranean coasts, major subsidence rates affect the Arno and Po deltas (Italy, ~10 and ~7 mm yr^{-1}, respectively), while rates by ~2 and ~1.4 mm yr^{-1} are reported in the deltas of Ebro (Spain) and Rhone (France), respectively (Besset et al. 2017). In the Venice lagoon, major subsidence rates affected the northern sector (3 to 4 mm yr^{-1}) (Tosi et al. 2018) while the in the Venice historical centre rates are expected to be 1 mm yr^{-1} in the next century (Zanchettin et al. 2021). In southern Italy, recent estimates based on Interferometric Synthetic Aperture Radar (InSar) and satellite data defined average subsidence rates by ~3 mm yr^{-1} in the Volturno plain (Di Paola et al. 2021) while rates comprised between ~6 and ~12 mm yr^{-1} were calculated in the coastal plain of Catania (Anzidei et al. 2021). Major subsidence rates were estimated in wider Thessaloniki plain (Northern Greece) coupling historical levelling and of recent Global Positioning System (GPS) data. This approach revealed an impressive subsidence of ~3.5 m over the second part of the 20th century (Psimoulis et al. 2007). In the Black Sea, data are only available for the Danube delta (Romania) which show long-term subsidence rates by ~1.5 mm yr^{-1} (Besset et al. 2017).

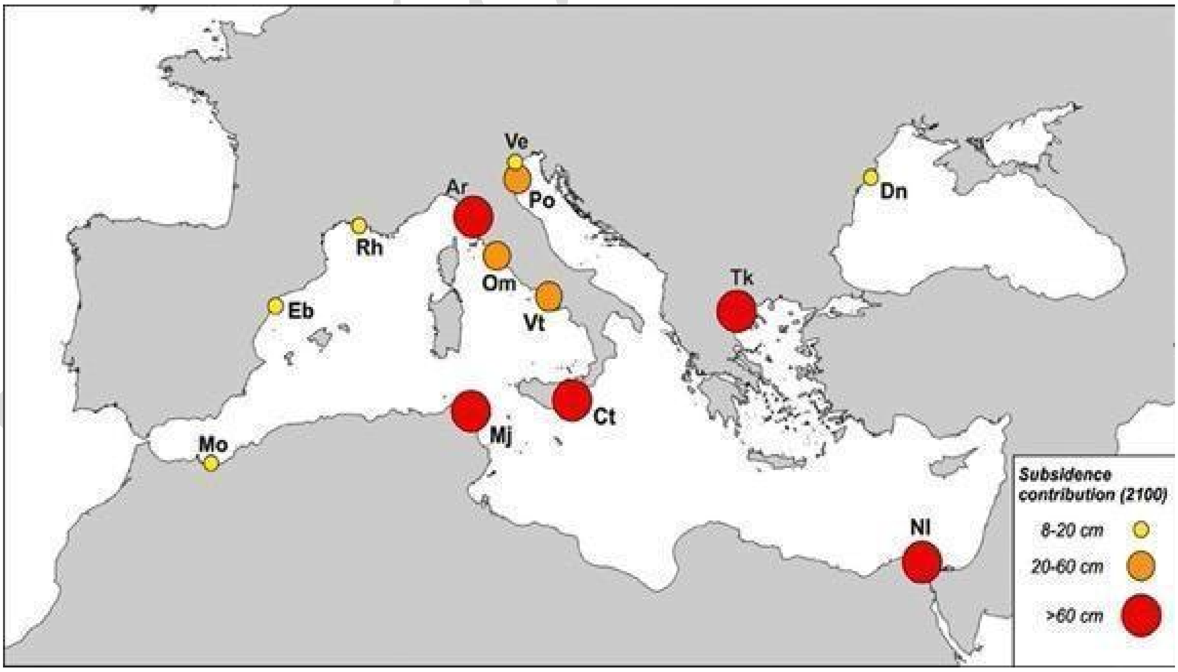

Figure 2.2 | Expected subsidence contribution to sea-level rise along some selected Mediterranean deltas and coastal plains. River acronyms: Ar: Arno; Dn: Danube; Eb: Ebro; Mj: Mejerda; Mo: Mouloya; Om: Ombrone; Nl: Nile; Po: Po; Vt: Volturno. City acronyms: Ct: Catania; Tk: Thessaloniki; Ve: Venice. (Figure obtained by combining data from Psimoulis et al. (2007), Besset et al. (2017), Saleh and Becker (2018), Anzidei et al. (2021), Di Paola et al. (2021) and Zanchettin et al. (2021)).

2.2.9 Geohazards (marine earthquakes, volcanic eruptions, submarine landslides) and tsunamis

Geohazards generated by neo-tectonic activity like marine and coastal earthquakes, volcanic eruptions and submarine landslides may generate tsunamis, or affect coastal aquifers, that may constitute a severe threat to coastal areas. To be holistic, in the coastal areas, any protection plan against marine hazards should consider geohazards in addition to the marine and atmospheric factors mentioned in the previous sections.

Geohazards are caused by geological processes that may dramatically change environmental conditions and present severe threats to coastal populations, offshore and onshore properties and offshore built infrastructures. Offshore, geological processes and human activities, for instance in connection with offshore petroleum exploration and production, can contribute to man-made geohazards.

Neo-tectonic activity may also affect coastal plain aquifers. The direct pressure transfer generated by the freshwater head in fractured lands may transport to the surface deep saline waters. Another mechanism is the hydraulic contact with pressurised brines flowing vertically along fault zones from deep reservoirs because of neo-tectonic activity. A third mechanism is when the salinity is incorporated in a saltwater-freshwater boundary zone, possibly as a result of brine pockets left behind by a receding sea (Re and Zuppi 2011). The neotectonics driven mechanism occurs at a slow rate, but the situation may change in the case of earthquakes.

In the Mediterranean, the largest and most destructive subduction zone earthquake with the moment magnitude (Mw)>8 occurred in 365 offshore of Crete Island (Shaw et al. 2008). It led offshore of Crete to an instantaneous uplift of Western Crete by more than 6 m and triggered a catastrophic tsunami that impacted nearly all coastal areas around the East Mediterranean Sea.

Submarine landslides

Submarine landslides occur when submarine slopes fail with destructive consequences. They have been studied in the Mediterranean (Camerlenghi et al. 2010), but their risk is small compared to other geohazards generated by earthquakes or volcanic eruptions.

Tsunamis

The geological tsunami time series comprises 135 events from 54 Holocene records across the Mediterranean (**Figure 2.3**). In the historical period, the most famous tsunamis occurred in 365, 1303, and 1908. The first two were caused by earthquakes in the Hellenic Arc, and the third occurred in the Messina Strait (Italy). Other devastating events occurred in –373 CE and 1748 in the Gulf of Corinth (Greece) and in 1783 in the Messina Strait. The most recent destructive tsunamis occurred in the Aegean Sea in 1956 with runup heights reaching 25 m (Papazachos et al. 1985) and the North of Algeria in 2003 with runup heights up to 2 m in the Balearic Islands (Alasset et al. 2006). All these tsunamis were generated by a strong earthquake (Soloviev, 2000; Papadopoulos and Fokaefs, 2005). Other big tsunamis were generated by volcanic eruptions, such as the 1650 eruption of the Thera (Santorini) volcano in the southern Aegean Sea. Thera also caused a remarkably strong tsunami around –1600 CE (Friedrich et al. 2006) and has been cited as contributing to the destruction of the Minoan civilization (Soloviev 2000). The European GITEC-TWO (Tinti et al. 2001) tsunami catalogue contains 94 reliably assessed earthquake-generated tsunami events during the last 2500 years (Sørensen et al. 2012).

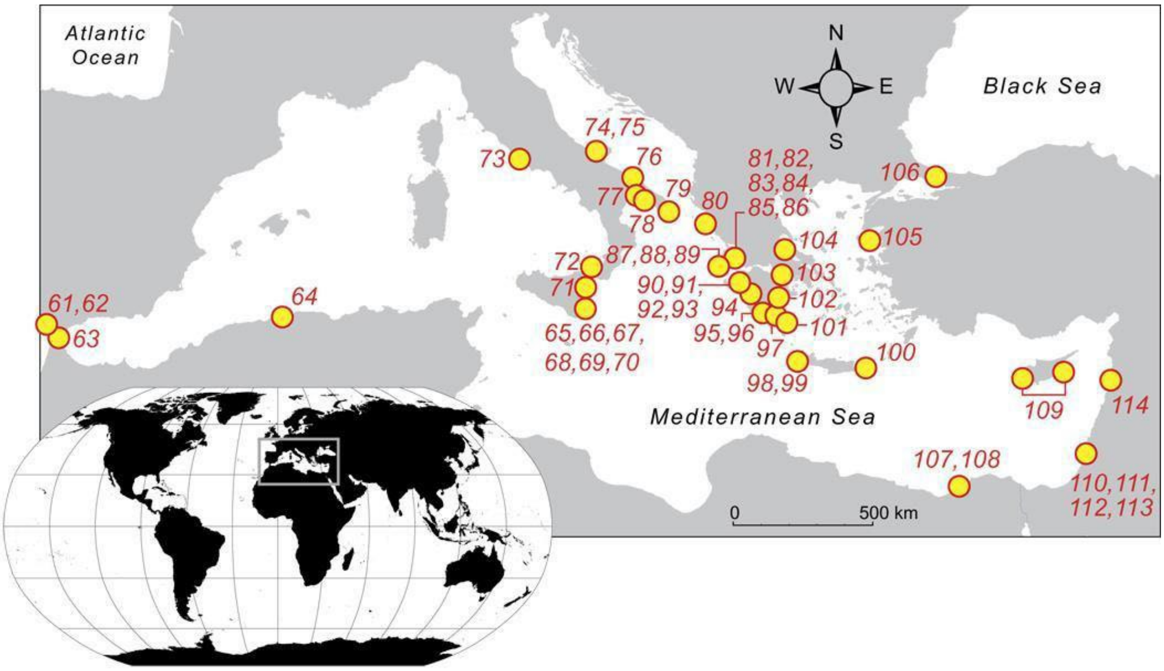

Figure 2.3 | Coastal sites affected by tsunamis since the Holocene. Numbers refer to the records mentioned in the original paper (Marriner et al. 2017).

2.3 Biological drivers

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.

2.3.1 Non-indigenous species

According to the International Union for Conservation of Nature (IUCN 2002, 2021) non-indigenous species - often termed 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 or human well-being.

Non-indigenous species are major agents of coastal biodiversity change, and mostly climate drivers interact to support their movement and 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 properties and ecosystem processes, prevent the delivery of ecosystem services (Grosholz 2002; Perrings 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; García-Gómez et al. 2020; MedECC 2020; Dimitriadis et al. 2021).

The Suez Canal provides 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). 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 2002), aquarium species trade (e.g., Hamza et al. 2022) and boats' ballast waters (e.g., Labruneet et al. 2019).

With over a thousand of non-indigenous species, the 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 a continuous invasion of exotic species (Azzurro et al. 2022b). 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 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 open sea (**Figure 2.4**). Wetlands, saltmarshes, seagrass beds and sandy beaches are some of the Mediterranean coastal ecosystems with higher potential of services delivery that interact by non-indigenous species. Moreover, these and other Mediterranean ecosystems are very rich in species and endemisms (Coll et al. 2010; Lejeusne et al. 2010).

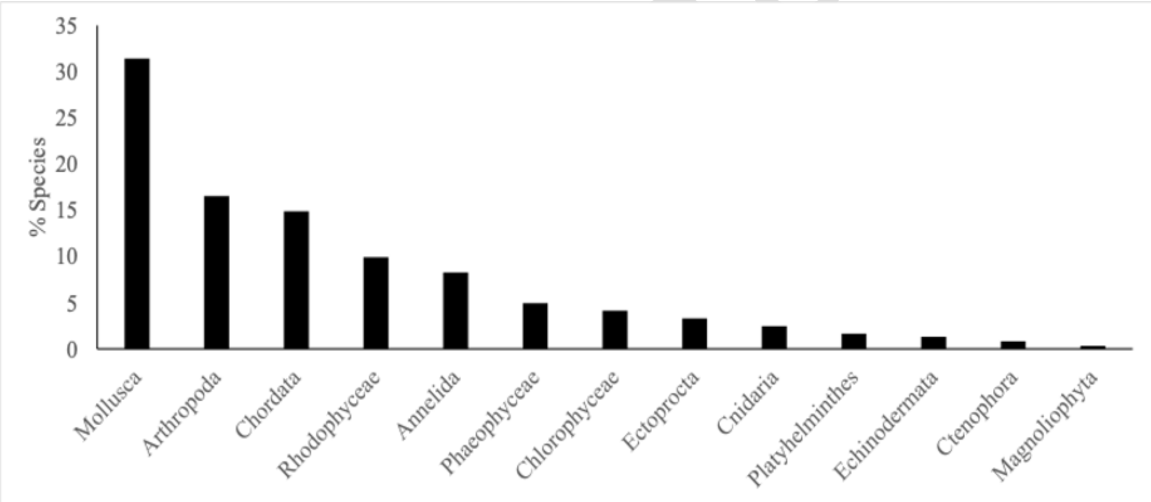

Figure 2.4 | Percentage of non-indigeneous species in the Mediterranean coast, presented by phylum. Adapted from Galil 2009.

2.3.2 Changes in the limits of species distribution

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 frame of the Mediterranean biota. However, most non-indigenous species enter into the Mediterranean through the Suez Canal, as already mentioned. As this is a man-made infrastructure, it is widely accepted that Red Sea immigrants that have established large, permanent populations in the Mediterranean. The most generally used definitions state that species entering through this pathway without direct human help cannot be regarded as genuine non-indigenous species. Instead, they are referred to as "newcomers" (see Evans et al. 2020) or "neo-natives" (see Essl et al. 2019).

Native species will also be affected by ocean warming, and therefore will lose competitive abilities to cope with biological drivers' effects, especially those caused by biological invasions. 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, termophilic species will show faster dispersal rates and population sizes 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).

With the construction of the Aswan Dam in 1969, the freshwater barrier between the Red Sea and the Mediterranean disappeared. The increase in temperature experienced in the last decades also reduces the water inflow to the Eastern Mediterranean and increases the 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 favor of thermophilic species. The waters coming from the Red Sea to 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 to 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 "tropicalization" or "demediterraneization" (Bianchi and Morri, 2003; Quignard and Tomasini 2000).

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, thus, contributing to species colonisation through the Strait of Gibraltar, but also to the dispersal of these and truly non-indigenous species within the Mediterranean.

Heat map representing the cumulative density of reported sightings of fishes of Atlantic origin, which are supposed to have entered the Mediterranean through the Strait of Gibraltar, without direct human assistance, is given in **Figure 2.5**. 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 fishes entering the Mediterranean between the 1950–2021 period (Azzurro 2022b). 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 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*) (IPCC 2022; Cooley et al. 2022).

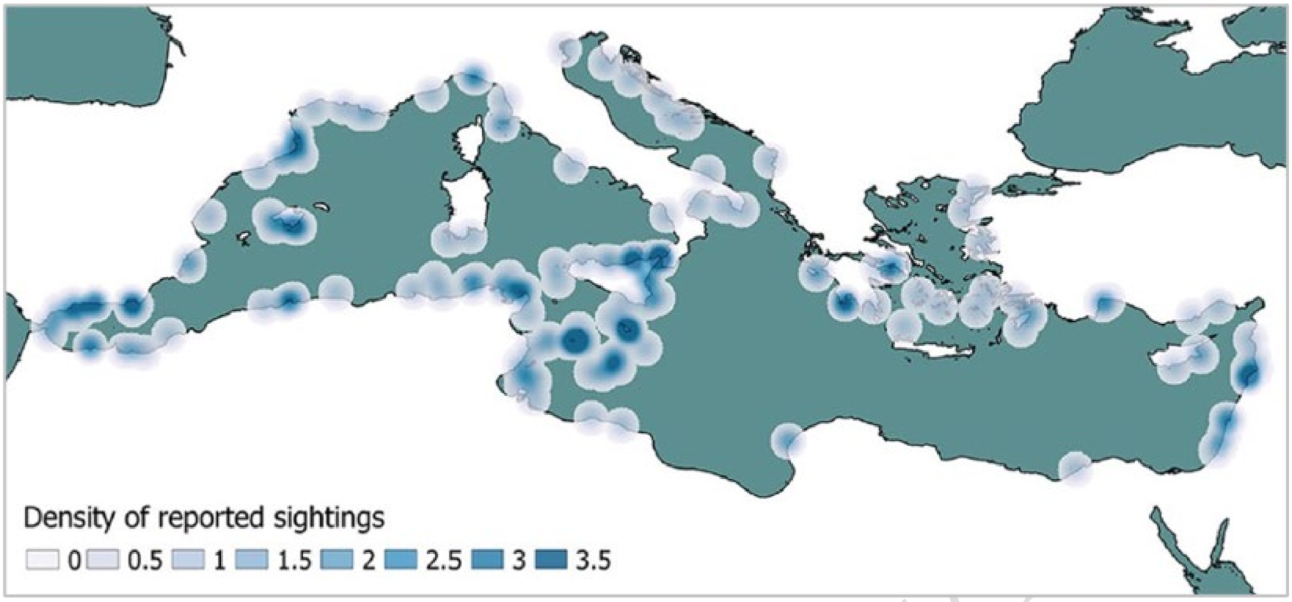

Figure 2.5 | Heat map representing the cumulative density of reported sightings of fishes of Atlantic origin (radius = 70 km), which are supposed to have entered the Mediterranean through the Strait of Gibraltar, without direct human assistance. Source: Azzurro et al. (2022b).

2.3.3 Jellyfish blooms

Although jellyfish blooms are natural events in marine ecosystems, their intensity and recurrence in the last decades 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 (e.g., stinging swimmers, interference with fishing, aquaculture and power plant operations) (Whiteman 2002; Carpenter 2004; de Pastino 2007; Owen 2006).

According to the Jellywatch program of the Mediterranean science commission (CIESM) there are a total of 23 main species of jellyfish occurring in the coasts of the Mediterranean and Black Seas that potentially can develop bloom events (CIESM GIS 2022). From these, there are 9 species of major concern either 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 four are non-indigenous.

The consequences of jellyfish blooms have concerned scientists and environmental managers due to the increasing incidence of these phenomena. 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 throughout the planet (e.g., Boero et al. 2008; Purcell 2012; Boero 2013; Condon et al. 2013; Canepa et al. 2014). 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 of 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 Mediterranean Sea is a semi-enclosed sea where pollutants dumped into the marine environment remain isolated. The primary pollution sources in Mediterranean coastal environments are atmospheric deposition, marine and coastal highway traffic, oil spills, solid wastes, agricultural residues, and urban and industrial effluents. Most pollution in the Mediterranean is land-based, followed by air and shipping-related pollution (MedECC 2020). The Mediterranean Sea has many coasts flagged as pollution hotspots due to coastal squeeze, intense industrialization, uncontrolled discharges of municipal and industrial wastewater, riverine 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 controlling phytoplankton communities. The availability of nutrients and their relative proportions controls 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 2.6**). In the North, the largest inputs occur in the Gulf of Lion, the Adriatic, and the Northern Aegean Sea (Karydis and Kitsiou, 2012; Viaroli et al. 2015). In the South and South-East, 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; El Kateb et al. 2018; Dorgham et al. 2019). Nutrient enrichment of coastal waters occurs via rivers and streams, atmospheric deposition, and submarine groundwater discharge (SGD). Riverine inputs are estimated at 1.9-2.6 Tg N yr^{-1} and 0.11-0.12 Tg P yr^{-1} (Malagò et al. 2019; 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; Romero 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 (Hallegraeff 2010; Glibert 2017) (*high agreement*), and this is a serious threat, notably in semi-enclosed bays and estuaries, coastal lagoons and deltas having high productivity and 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 (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 (Kanakidou et al. 2020; Rodellas et al. 2015).

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; 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, riverine 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 (Ludwig et al. 2010; Powley et al. 2018; UNEP/MAP and Plan Bleu 2020) (*high confidence*). 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 (Powley et al. 2018) (*medium confidence*).

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-economical developments including unsustainable agri-cultural practices), is *likely* to impact most of the Mediterranean Basin through increased water scarcity *(high confidence).* Water scarcity challenges water quality because lower water 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, and this trend is expected to continue (Perennou et al. 2020) (*high confidence*).

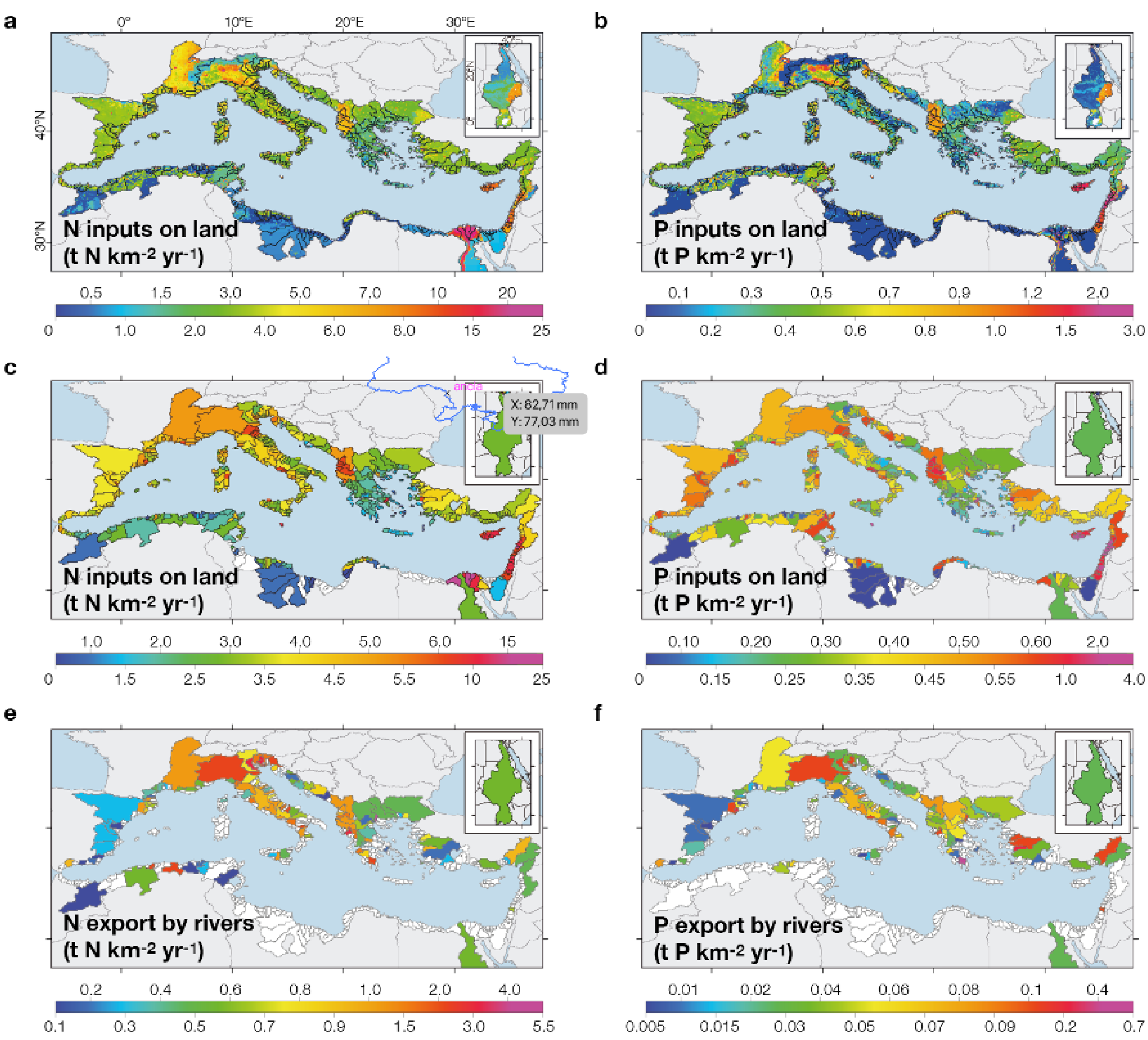

Figure 2.6 | Total land inputs and river exports of N (on the left column) and P (on the right column) to the Mediterranean Sea. a-b: spatial variability of land inputs within the basins (data at 5 arc min resolution); c-d: land inputs averaged per river basin; e-f: river exports averaged per river basin. About 10-25% of all N land inputs and 8-12% of P inputs are directly exported by rivers to coastal seas (modified from Romero et al. 2021).

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 those trace elements of major concern, Technology-Critical Elements (TCEs) such as platinum (Pt), tellurium (Te), germanium (Ge), lanthanum (La) and gallium (Ga), release from emerging technology and introduced into Mediterranean coasts (Abdou et al. 2019; Romero-Freire et al. 2019). Human activities enriched the metal trace elements in Mediterranean coasts (Belivermiş et al. 2016; Tovar-Sánchez et al. 2016; MedECC 2020). Urban and industrial wastewaters, atmospheric deposition and run-off from metal contaminated sites constitute the major sources of toxic metals in coastal areas (MedECC, 2020; Trincardi et al. 2023).

In marine ecosystems, the hotspots of lead, mercury and cadmium were essentially located on the north central and southeastern shores of the Mediterranean Basin (MedECC, 2020). The principal sector contributing to the release of heavy metals in South Mediterranean countries is the manufacturing of refined petroleum products. For the Balkans and Türkiye, the main contributing sectors are refining petroleum products, the tanning and dressing of leather 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 Report, 2021). In the western Mediterranean coastal waters, high Cd, Pb, Hg, and Ni levels were reported in the Alborán Sea, northwestern Mediterranean, Tyrrhenian Sea, North Africa, respectively, whilst the rest of the western Mediterranean displayed moderate pollution with metals (Benedicto et al. 2011). In the east Mediterranean coasts, the highest concentrations of metals were reached in the pollution hotspots, heavily impacted by human activities. For instance, highest Pb, Cu and Zn were detected in the sediment samples of Alexandria harbor (Egypt) while the highest As, Cd, Cu, Hg, Pb, Zn 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) concentrations are twice as high in the waters of the West compared to East Mediterranean (*high confidence*). MeHg is biomagnified in marine food webs more efficiently compared to Hg. MeHg concentrations are higher in marine food in West compared to East (*medium confidence*) (Cossa et al. 2022).

Levels of heavy metals (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 the 10% of the stations, Pb levels in mussels were above the maximum concentrations set by the European Commission (European Commission 2006). Concerns with regard to heavy metals are found in the coastal sediment compartment for Pb and total Hg, indicating an impact from these chemicals. For total 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 2017,2020).

For EU countries in the Mediterranean, trends in the release of toxic metals indicate a general decrease except Malta (*high confidence*). In the temporal variability point of view, metal concentrations decreased in the North thanks to the regulatory measures (*high confidence*) (Santos-Echeandía et al. 2021; Tavoloni et al. 2021). However temporal increment trends have been reported in some coastal areas such as Venice (Italy) and in the Nile delta (Egypt) (Mandour et al. 2021; Morabito et al. 2018).

2.4.3 Plastics

Disposal of manufactured and processed solid waste in the marine environment, known as marine litter, is one of the major drivers in Mediterranean coasts (Boucher and Bilard 2020; MedECC 2020; UNEP/MAP and Plan Bleu 2020). Plastics are accounting for up to 95–100% of total floating marine litter and more than 50% of seabed marine litter (UNEP/MAP and Plan Bleu 2020). The floating plastics squeeze along the coasts due to human activities (tourism, fishing activities, industrial and municipal wastewater) and unique hydrodynamics of this semienclosed basin (Trincardi et al. 2023). In numbers, plastic production has reached 368 million metric tons in 2019 across the world, which is remarkably high. As a matter of fact, this production is increasing abundantly through the years (PlasticsEurope 2020; Patrício Silva et al. 2021). 1.5 to 4% of the global production of plastic ends up in the oceans *(medium confidence)* (Maes et al. 2018; Kane et al. 2020; Shabaka et al. 2020).

Due to its high coastal population density and its connection with densely populated rivers along with the Atlantic Ocean, the Mediterranean Sea is considered as one of the most polluted areas with plastics across the globe *(high confidence)* (Boucher and Bilard 2020; MedECC 2020). This basin receives around 200,000 tons of plastic every year (Cózar et al. 2015; Suaria et al. 2016; Boucher and Bilard, 2020; Zayen et al. 2020; Ben Ismail et al. 2022; Kostas et al 2022). In the Mediterranean, 67% of all the plastic particles crossing the land-source buffer zones remain in the coasts (Baudena et al. 2022). Mersin (Türkiye), Tel-Aviv (Israel), Syria, Algiers (Algeria), Barcelona (Spain), Bizerte (Tunisia), Alexandria (Egypt) and Po delta (Italy) are the most polluted Mediterranean coasts with plastic (**Figure 2.7**). Daily plastic debris accumulation on the coastline (kg km^{-1}) is the highest in Türkiye's Cilicia region (Mersin) followed by Barcelona and Tel-Aviv (Baudena et al. 2022; Liubartseva et al. 2018). Italy (12.6 kT y^{-1}) and Türkiye (12.1 kT y^{-1}) accumulate the most coastline plastic debris each year due to length of coastlines and the elevated plastic quantity in their coastal waters (*high confidence*) (Liubartseva et al. 2018; Baudena et al. 2022).

In decreasing order, Egypt, Italy and Türkiye are the first three countries releasing plastics (macro and microplastic) into Mediterranean coasts. Annual plastic leakage into the Mediterranean coastal area is between 230,000–260,000 tonnes (Boucher and Bilard 2020; UNEP/MAP and Plan Bleu 2020). 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 and improved waste management, the leakage is likely to decrease by 2040 (Boucher and Bilard 2020). In all projections, coastal plastic inventory is likely to increase (*high confidence*) due to the fact that plastic degradation is a very slow process and microplastics bury in deep sediment (Belivermiş et al. 2021; Simon-Sánchez et al. 2022).

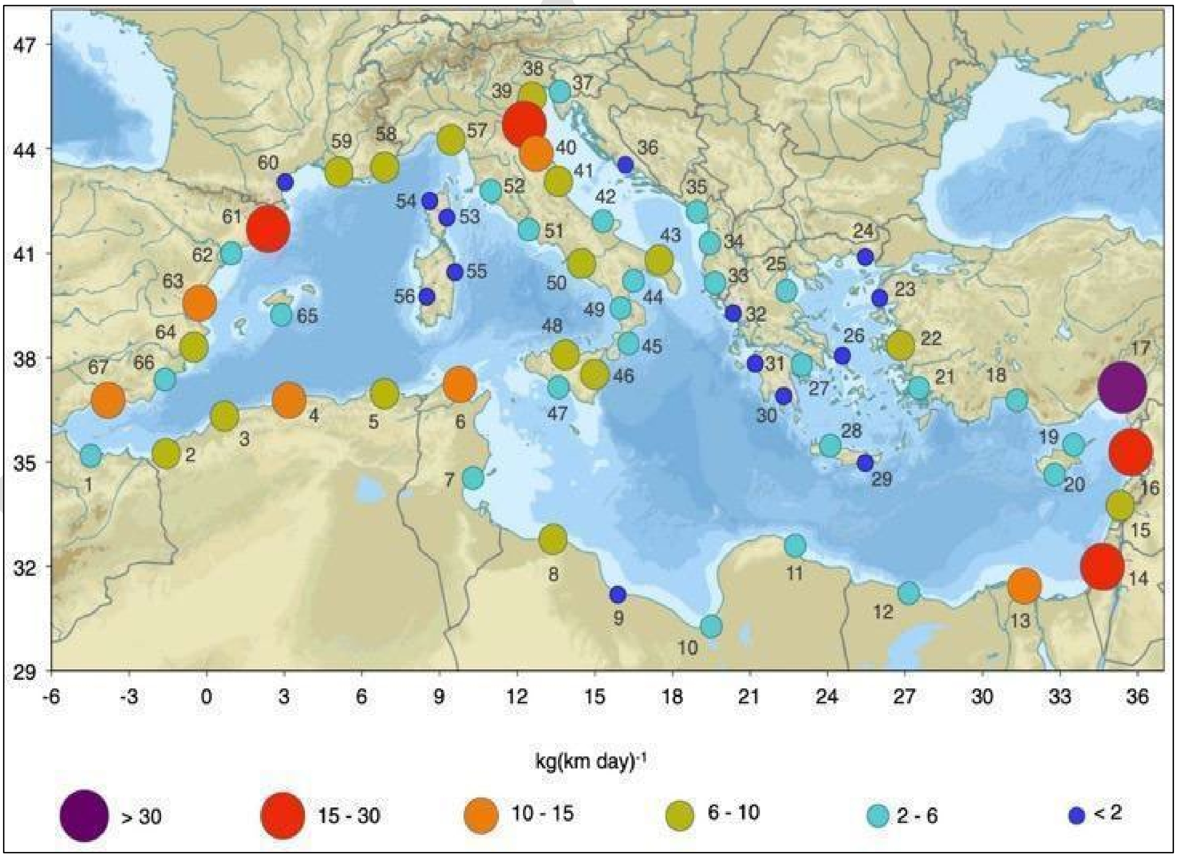

Figure 2.7 | Plastic debris fluxes (kg km day^{-1}) onto the Mediterranean coastlines (Liubartseva et al. 2018)

2.4.4 Emerging pollutants

The term "emerging contaminants" (ECs) refers to a diverse group of thousands of chemicals and xenobiotics, the biological effects of which are unknown and whose existence in the environment has only recently been studied and monitored (MedECC 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, phytoestrogens, perfluorocarbons, and pharmaceuticals (painkillers, antibiotics, and antidepressants) that are products of cutting-edge technology (Chacón et al. 2022; UNEP/MAP 2020). Runoff and seepage from landfills, animal waste, aquaculture, hospitals, industrial wastewater, and home wastewater all emit ECs into the coastal environment (Li 2014). Low geographical variability of ECs in the Mediterranean Sea suggests that they are emanated from diffuse pollution sources such as wastewater treatment plants (WWTP) and runoffs from agricultural areas (Brumovský et al. 2017). Among the wide variety of ECs, PPCPs (pharmaceutical and personal care products) are the most concentrated ones in the three river basins in the Mediterranean Sea. In these basins, the urban discharges are the primer source of pharmaceuticals like ibuprofen. Pesticides like chemicals are associated with agricultural activity while PCBs (polychlorinated biphenyls) and PFOS (perfluorooctane sulfonic acid) are associated with industrial facilities in Mediterranean coasts (Köck-Schulmeyer et al. 2021).

Northern Mediterranean coasts are polluted with ECs more severely than the South due to the abundant point source in the northern coast. However, ECs are elevated in the rivers of some Mediterranean countries, like Tunisia, Israel, Türkiye, Spain and Palestine (Wilkinson et al. 2022). Active pharmaceutical ingredients (APIs) are elevated due to discharge of untreated sewage as such in Tunisia and Palestine. In 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 to not detected to 3000 ng L^{-1} in seawater. Among the 43 drugs, pharmaceuticals highlighted thirteen compounds that are cause for concern in Mediterranean coasts, such antibiotics and anti-inflammatories (Desbiolles et al. 2018). Anti-inflammatories and antibiotics are the most dominant types of PPCPs in the East and South Mediterranean (Ouda et al. 2021).

Most of the Mediterranean countries had no published data regarding the concentration of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) for their coasts. Italy, France, Spain and Egypt were flagged as the main polluted Mediterranean countries with PAHs and PCBs. The highest PAHs and PCBs levels are around harbour and industrial areas, as the case of Lazaret Bay (France), Naples Bay (Italy), Gulf of Taranto (Italy) (Di Leo et al. 2014; Merhaby et al. 2019). Shipping is one of the main sources of oil pollution in Mediterranean coasts. About 90% of tanker spills in the Mediterranean Sea occur near the coastlines. In the East, the Levantine Sea coast is the hotspot of oil pollution (Polino et al. 2021) due to the regional political instability and extensive coastal oil facilities (Levin et al. 2013).

Overall, the levels of ECs, specifically PCDD, polychlorinated dibenzofuran (PCDF), PAH, volatile organic compounds (VOCs), in the Mediterranean have generally declined (except Greece) (EEA-UNEP/MAP Report 2021). Persistent organic pollutants (POPs) in the coast will *likely* decline by means of the improvement of wastewater treatment and outlawing of certain compounds (Piante and Ody, 2015). However, occurrence, safe levels and ecotoxicological properties of some known and most "new" ECs are unclear (*high confidence*). In addition, there is an increasing trend in maritime transport, port activity and the production of offshore gas and oil in the Mediterranean Sea

(Piante and Ody, 2015), which will *likely* diffuse ECs in Mediterranean coasts. The data regarding the occurrence and the levels of ECs in the Mediterranean coasts is very limited, particularly in the East and South.

2.4.5 Air pollution

Air quality in Mediterranean coasts are negatively affected by airborne particulate matter (PM2.5–PM10; particulate matter diameters of 2.5 and 10 microns or less, respectively) and gases from northern and eastern Europe, desert dust from Sahara and surrounding arid regions, biomass burning (forest fires), in addition to local pollution sources such as ports, vehicular traffic, industrial and residential heating (MedECC 2020; Perrone et al. 2022). Energy consumption, road transport, shipping emissions and the manufacturing and extractive industry are the principal sources of air particulate matter in the North and the East of the Mediterranean (MedECC 2020).

Air pollutant monitoring and related data are scarce in the South and the East of the Mediterranean coast (except for Greece and Türkiye) compared to the North. Having said the data is scarce in the South, 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 Turkish and Italian coastal areas displayed PM2.5 and PM10 concentrations higher than EU limit values. Several local studies show that PM concentrations in the southern Mediterranean region are much higher than the EU and World Health Organization (WHO) limit values (Naidja et al. 2018). Emissions from road traffic, resuspension of road dust and natural contributions are principal sources of air particles in southern Mediterranean coasts (Naidja et al. 2018).

The eastern Mediterranean and the Middle East are characterised by high background tropospheric ozone concentrations (Lelieveld et al. 2002, Georgiou et al. 2022), since they are affected by polluted air masses from various sources such as the eastern and central Europe, and the Middle East (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 Turkish coasts (*medium confidence*). Concentrations of NO_2 and Benzo[a]pyrene (BaP) are higher in Greek and Italian coasts, respectively, than the limit value set by the EU (EEA 2021, 2022). Cyprus faces challenges with the exceedance of air quality limits and compliance with European regulatory standards (Georgiou et al. 2022; European Environment Agency, 2019).

15% of global shipping activity and around 18% of global crude oil shipments take place in the Mediterranean Sea (Carpenter and Kostianoy 2018). Luxury cruise ships emit up to 18, 10, and 41 times higher SO_X than all of the passenger vehicles (including cars) respectively in Spain, Italy, and Greece, top cruise ship polluted countries in Europe (Transport and Environment 2019). However, the 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 Mediterranean Sea (Fink et al. 2023). Shipping contributions to PM2.5 or PM10 emissions (between 0.2% and 14%) is larger in the Mediterranean area compared to northern Europe (Contini and Merico 2021). Among the world harbours (mostly European harbours), Taranto (Italy) has the highest PM10 concentration (Sorte et al. 2020).

Emissions of all key air pollutants in the EU countries have been declining since 2005. Emissions of sulphur dioxide and nitrogen oxides fell by 76% and 36%, respectively since 2005. PM2.5 and PM10 emissions fell by 29% and 27% respectively since 2005 across the northern and eastern Mediterranean (EEA 2021, 2022). However, the release and levels of air pollutants are *likely* to increase in Mediterranean coasts due to the upward trend in port activity, maritime transport, offshore gas and oil production (Piante and Ody 2015).

2.5 Social and economic drivers

2.5.1 Current and future socio-economic trends across the coastal region

Mediterranean countries are currently (2020) home to more than 540 million people, with a high concentration of urban settlements and infrastructure near the coast (Ali et al. 2022), see **Figure 2.8**). Mediterranean communities have developed lifestyles adapted to non-dynamic water levels, as the coastline has been relatively stable compared to the rest of the world due to low energy conditions, except for erosion at the local level (Vafeidis et al. 2020). Therefore, the Mediterranean population currently lives in close proximity to the coast. However, this results in a high concentration of population in the coastal zone (around one-third of the Mediterranean population lives near the coast (UNEP/MAP and Plan Bleu 2020). The Mediterranean Low Elevation Coastal Zone (LECZ, area below 10m) hosted more than 41.8 million people (share 8.9%) in 2010 (Reimann et al. 2018a). Climate-related coastal exposure is higher in southern and eastern Mediterranean countries due to higher urban population density, which is three orders of magnitude higher than in the North (Reimann et al. 2021).

The total population in the Mediterranean coastal region will continue to increase in the future under all socio-economic scenarios and that exposure to sea-level rise and coastal hazards is high in the North as well as in the South and the East (see **Figure 2.8**). In the northern Mediterranean, Shared Socioeconomic Pathway (SSP) 5 leads to the highest coastal population (15.2 million), while the coastal population declines under SSP3 (6.5 million) by the end of the century. In contrast, SSP3 leads to the highest coastal population in the southern and eastern Mediterranean (over 100 million), whereas the lowest coastal population is observed under SSP5 (42.7 million) (see **Figure 2.8**) (Reimann et al. 2021).

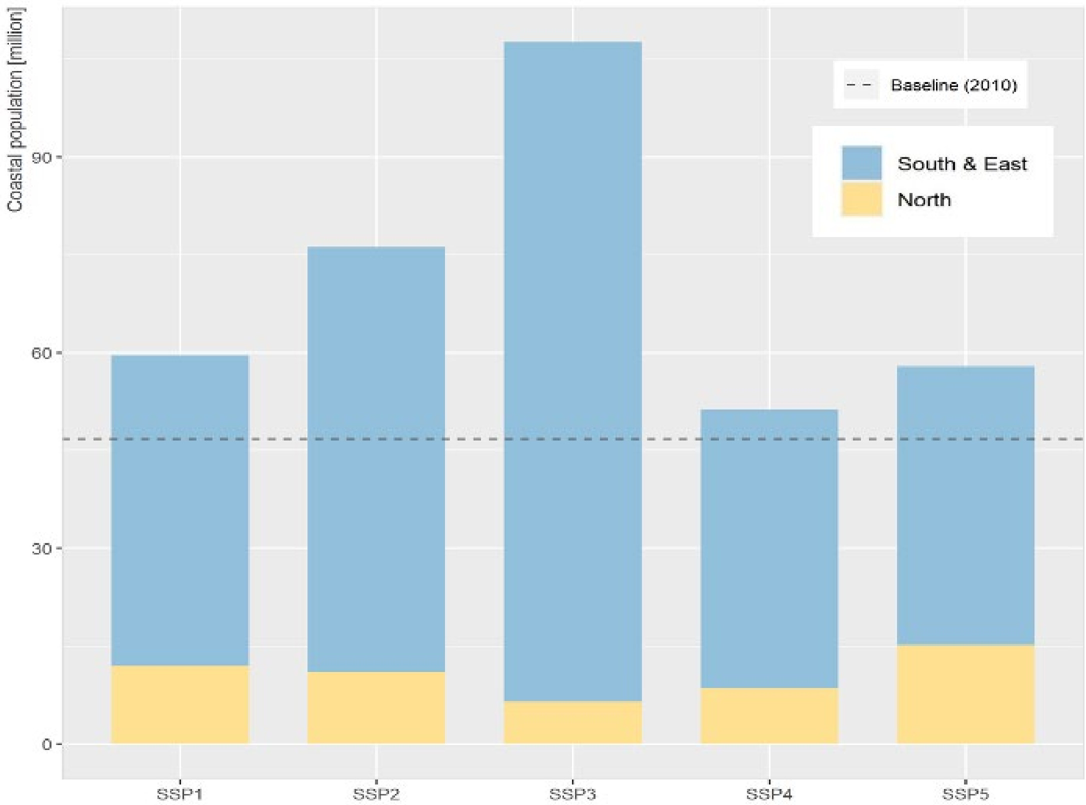

Figure 2.8 | Mediterranean Coastal population in each SSP in 2100. Based on Reimann et al. 2021 (Coastal = LECZ based on MERIT, population in 2010 is based on Global Human Settlement Population Grid; GHS-POP)

At the country level, Egypt, Libya, Morocco and Tunisia are currently most exposed to sea-level rise due to their large coastal floodplains and rapid coastal population growth (World Bank 2014; Ali et al. 2022) (*medium confidence*). According to Neumann et al. (2015), Egypt is the county with the highest population in the LECZ along the Mediterranean coast (26 million; 38% of its total population). In 2000, the population density in the Nile delta was 1075 people km^{-2}, comparable to the population density of Japan or Bangladesh in the LECZ. Population density along the Egyptian coast is expected to increase further to 1,902 people km^{-2} by 2030 and 2681 people km^{-2} by 2060 (Neumann et al. 2015). The lowest total number of LECZ population is observed in EU candidate countries, namely Bosnia and Herzegovina, Montenegro, Albania and Türkiye (Reimann et al. 2018a).

Additionally, urban expansion and the associated concentration of wealth production are increasing faster in low-lying coastal regions than in the hinterland worldwide (Seto et al. 2011). Mediterranean countries are characterized by a large and growing urban population (Dos Santos et al. 2020), so rapid coastal urbanization is leading to increased exposure of human settlements and infrastructure to sea-level rise and its associated hazards (UNEP/MAP and Plan Bleu 2020). Two out of three people already live in urban areas in Mediterranean countries, which is higher than the global average (Dos Santos et al. 2020). The United Nations Human Settlements Program projects that by 2050, the urban population will grow to about 170 million people in countries on the northern coast (140 million in 2005) and to over 300 million in the South and the East, where the population was 151 million in 2005 (UNEP/MAP 2016). According to Wolff et al. (2020), urban expansion in the coastal floodplain increases in all regions (however only 10 Mediterranean countries were considered in the study) by 2100, leading to a substantial increase in coastal exposure. For example, depending on the SSP scenario assessed, urban extent increases by 67% (2075 km^2) for Italy, 104% (2331 km^2) for France (Mediterranean coast only) and 86% (691 km^2) for Greece in the extended LECZ (E-LECZ = area below 20 m that is hydrologically connected to the sea) between 2012 and 2100. Further, coastal urban development is driven by tourism in the Mediterranean. In 2016, more than 360 million international tourist arrivals per year were registered in the Mediterranean, mainly concentrated in coastal zones, which represents nearly one-third of world tourism (UNWTO, 2019).

The Mediterranean coastal regions are characterised by a high socio-cultural wealth resulting from the enormous cultural and socioeconomic diversity around the basin, which represents an important cultural, economic and/or heritage asset for the economy (e.g., tourism) and society (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 thus 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 (Vafeidis et al. 2020) (*high confidence*).

2.5.2 The economic use of the coast

2.5.2.1 Tourism and cruising

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 2020).

Over half of the EU's tourist accommodation establishments are located in coastal areas. Cruise infrastructures remain 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 Northern Africa; the rest on the eastern Mediterranean side (Castillo et al. 2022).

However, COVID-19 pandemic and growing geopolitical conflicts are increasing threats for the tourism industry globally, and particularly in the Mediterranean. The tourism sector had 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 infrastructures (Asero and Kasimati 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 over tourism due to the many visitors, who stay only a short amount of time (Asero and Skonieczny 2018). 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

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, resources' 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 that host at least one offshore platform) being located in the eastern side of the Mediterranean Sea (**Figure 2.9, under consideration and drafting**).

In contrast with other world regions (e.g., the North Sea), decommissioning has not been a major issue yet, with main exploitation projects still ongoing thus 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 thus making many Mediterranean exploitation areas quite competitive in respect with other offshore fields (and investment costs lower than in other areas).

Sediments supply to coastal areas

Considering sediments and dams it is worth noticing that the Mediterranean drainage basin incorporates more than 160 rivers, mainly small ones, most of them distributed on the European side of the Mediterranean coast. 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". Same authors highlight how about 46% of the total length of the Mediterranean coastline has been formed by sediment deposition and many Mediterranean deltas have prograde in recent times. Dams within the Mediterranean region have also affected river sediments but most of them are located in areas not directly connected to the Sea, normally used for electricity generation. 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 (e.g., Nile delta, Egypt). From the European side, dams' location and their impact on the environment are monitored by the European Environment Agency (see **Figure 2.10**) that focuses on understanding their value as water reservoir 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 of renovation, and coastal impact of river flows.

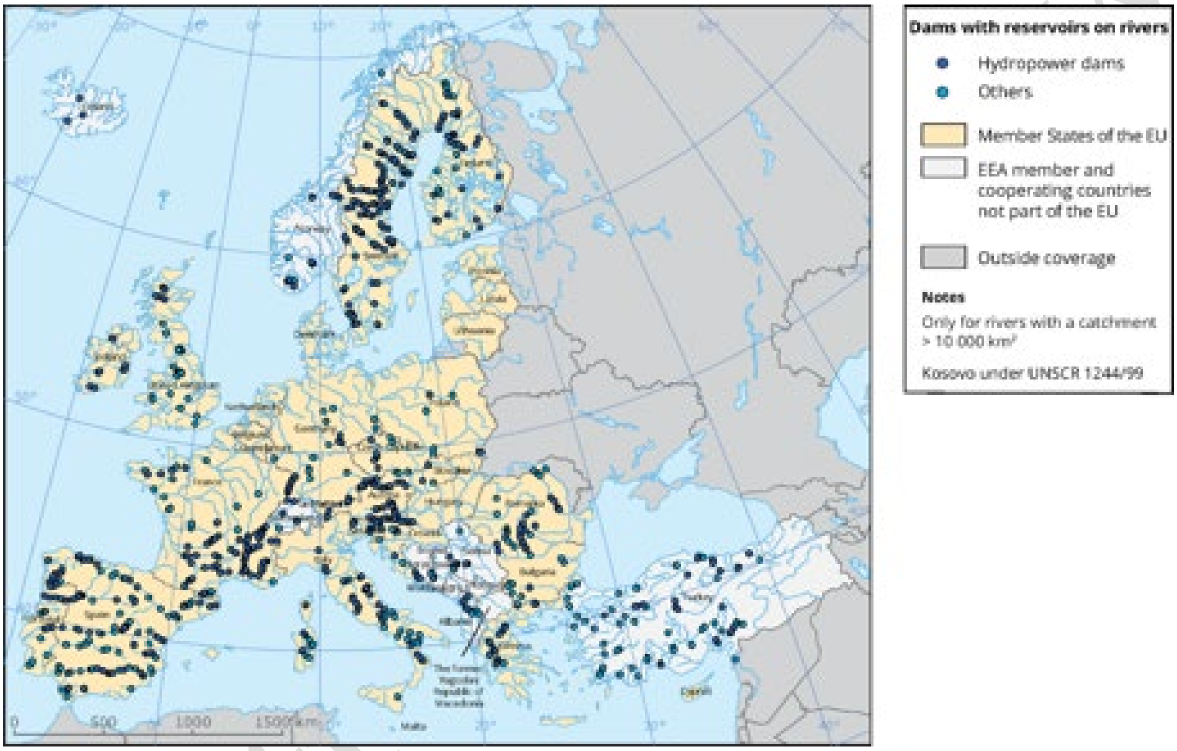

Figure 2.10 | Map of dams in Europe (source: EEA 2023).

2.5.2.3 Sea water desalination

The ongoing decrease in precipitation and increase in average annual temperatures include smaller effective meteoric contribution, lower discharge of the rivers and higher evapotranspiration. On the coastal areas, this causes a general deterioration of water quality in aquifers due to freshwater salinization (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 region, the production of desalinated seawater is projected to be thirteen times higher in 2040 than 2014. (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. 2020a). At the same time, it represents a reliable and constant supply of freshwater in water-scarce regions. Its relatively high cost appears more and more acceptable as the costs of conventional water supply (including impacts on ecosystems caused by freshwater abstractions and greenhouse gas emissions) due to the needs of pumping, storage and treatment of freshwater increase. The Mediterranean has already 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} of desalination capacity mostly concentrated in Spain and, to a lesser extent, Italy and other countries (Addamo et al. 2022), accounting for almost 10% of the global capacity. As a hotspot of climate change, projected to face more and more severe water scarcity, Mediterranean countries will likely need to build several new plants in coastal areas throughout the region. This fact is related to significant greenhouse gas emissions unless adequate plants to function with renewable energy sources are designed (Pistocchi et al. 2020b; Ganora et al. 2019). Benefits increase when coupling desalination with water reuse (Pistocchi et al. 2020b).

2.5.2.4 Aquaculture and fisheries

Fishery is an activity leading to harvesting of fish. It may involve capture of wild fish or raising of fish through aquaculture (FAO 2023, entry: 98327). Aquaculture is based on the cultivation (of fish, crustaceans, mollusks, algae and aquatic plants of value) in sheltered coastal or offshore waters, as well as in proximity of 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. In relation to 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, Spain and Italy 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 (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) (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 (Ben Rais Lasram et al. 2010) (*very high confidence*). 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 (Cheung et al. 2016) (*high confidence*).

2.6 Final remarks

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

The dramatic and unexpected events of recent years (e.g., the Covid 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 exchanges, 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 the pollution and biological drivers, the comprehensive data set including all coasts of the Mediterranean is very scarce (*very high confidence*) due to unequal socio-economic structures of the countries across Mediterranean coasts, political instability and lack of international cooperation. In addition, each region of the Mediterranean coast is exposing variable concentrations of pollutants and there are no limit and/or threshold levels of pollutants accepted by all Mediterranean countries (*high confidence*). Large-scale (including all Mediterranean countries), periodic and standardized pollution and biological monitoring campaigns 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* decline pollution on Mediterranean coasts.

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3 Impacts and risks

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3.0 Executive summary and/or key messages

This chapter makes a comprehensive overview of the main coastal impacts and risks affecting the Mediterranean coasts. Due to their importance and potential impact on the Mediterranean coastal system, main covered risks are erosion, flooding, water-related (e.g., saltwater intrusion and pollution) and biological ones. They are analysed at different time scales associated with drivers of different origin, as described in Chapter 2. The different risks under current conditions and under the effect of climate change are characterized, providing the respective magnitude for the Mediterranean and identifying coastal hotspots. The main impacts induced by analysed drivers and hazards are characterised by considering their potential effects on the economy (related to main economic sectors in the Mediterranean coastal zone such as tourism, agriculture and fisheries), ecology (impacts on representative habitats and ecosystems such as deltas, wetlands and seagrass) and on the human system (cultural heritage and human health).

It has to be considered that some of the economic activities potentially affected by analysed hazards such as coastal tourism are also a driver of impacts along the Mediterranean coastal system. The current picture for the basin is a coastal fringe subjected to multiple hazards, with a large exposure due to the socio-economic-cultural setting of the Mediterranean with a high concentration of population and assets and a relatively high vulnerability due to the reduction in natural coastal resilience.

Key messages

Coastal erosion

- Under current conditions, the Mediterranean coastline is dominated by long-term erosion, with a median projected shoreline retreat by 2100 with respect to 2010 of 17 m, with *very likely* range between –32 m and –1 m. This behaviour presents a large spatial variability, with the western basin concentrating the most important erosional regional hotspots, which are mainly located in river mouth areas and coastal stretches around harbours and other coastal infrastructures.
- The erosive behaviour will increase under the effect of climate change, as SLR will induce a generalized induced shoreline retreat (*very high confidence).* The estimated median value of shoreline retreat for the Mediterranean shoreline with respect to 2010 is –17.5 m and –23 m for the year 2050 under the IPCC AR5 RCP4.5 and RCP8.5 scenarios respectively, increasing to –

40 m and –65 m respectively by the year 2100. Whereas the shoreline retreat is certain to occur, the computed induced rates have a significant uncertainty associated to the used models.

- In the absence of adaptation and protection measures, Mediterranean beaches will continuously erode during the next decades, and in urbanised areas, where the coast is limited by physical barriers, this will lead to the progressive narrowing and, eventually, disappearance of beaches. This represents a high risk for intensive sun-and-beach tourism areas due to the expected decrease in beach carrying capacity and its associated economic consequences.
- The progressive narrowing of beaches will reduce the degree of protection provided to existing infrastructures along the coast, with the corresponding increase in the risk of storm induced damages. Thus, even in spite of the absence of any significant increasing trend in storm intensities and frequency, storm-induced damages will increase (*very likely*) during the next decades along the Mediterranean coast.

Coastal flooding

- Coastal flooding in the Mediterranean due to the impact of coastal storms is mainly controlled by waves due to the relatively low magnitude of surges, with the exception of some protected areas such as Venice (Italy) where surges play a dominant role. The most exposed areas are waterfronts and the more seaward parts of urban developments. The areas of greatest risk have a large spatial variability controlled by the local storm climate and the extent and dimensions of existing natural and human defences. In the future, SLR will induce an increase in frequency and magnitude of storm-induced flooding along the Mediterranean coastal zone due to an increase in the total water level at the shoreline (*very likely*), leading to an increase in the existing risk in the absence of adaptation/protection measures. This effect will be more important in low lying areas and it will be enhanced by the reduction in protection due to beach erosion.
- SLR will result in the gradual and permanent inundation of low-lying unprotected areas. Throughout the Mediterranean basin, the areas that will be most affected are deltas and coastal plains, which are also subject to subsidence that can locally significantly increase relative sea level rise. These areas are often home to the highest natural values along the Mediterranean coastal zone, while being also exploited for agriculture, which convert them in the highest risk areas to RSLR.
- The Mediterranean basin is one of the areas in Europe where disastrous flash floods are more frequent, mainly affecting river mouths and coastal areas, due to local climate and topographic conditions on the one hand, and the existing high population and urban settlements in flood-prone areas. In the future, in the absence of adaptation, a higher risk is likely to occur due an increase in heavy rainfall episodes due to climate change and the continuous growth of urban areas along the coastal zone, although showing a large spatial variability (*medium confidence*).
- The Mediterranean coast is one of the highest risk areas in Europe to compound flooding due to co-occurrence of heavy rainfall and high-water levels. The expected evolution of these events under climate change will be affected by the increase of both hazards although it shows a large spatial variability in their occurrence without a clear trend regarding their intensity (*medium confidence*).

Tsunamis and meteotsunamis

- Due to the high seismicity of the Mediterranean basin, the short travel times of tsunami waves to the coast from source areas and the concentration of population and assets along the coastal zone, tsunamis are a significant threat for the Mediterranean coastal zones despite their low frequency, with the eastern basin being the most affected one.

- Meteotsunamis occur regularly on the Mediterranean coast and show large spatial variability, with their highest intensities in bays and inlets where resonance is favoured. Because of this, the greatest damage and, consequently, the areas of highest risk are concentrated in local hotspots where existing coastal infrastructures and developments are not adapted to accommodate large changes in sea level. Despite this, hazard assessments are only available for a few areas, while risk assessments are lacking.

Freshwater resources scarcity

- In absence of appropriate adaptation and protection strategies, the quantity and quality of freshwater resources in the coastal areas will decline, reducing the water available for the future uses (*very likely*).
- Maintaining the socio-economic activities related with the significant urban, agricultural and/or industrial development in Mediterranean coastal areas, which require to supply significant freshwater demands, will be a challenging issue which will be exacerbated due to seawater intrusion in coastal aquifers. In the future, associated risks will be amplified due to the expected reduction in aquifer recharge, sea level rise, the increase in water demands and the frequency and severity of droughts.
- The use of unconventional water resources generated by desalination will reduce the risk of water scarcity and their socio-economic implications, but it may increase the risks of environmental impacts, especially on coastal ecosystems (e.g., adverse impact due to brine water discharge) and will increase associated CO_2 emissions.

Coastal pollution risks

- Water pollution along the Mediterranean coast is mainly generated by land-based point and diffuse sources (80 %) due to the existing high urbanization of the coastal zone, with ship-induced and air pollution contributing the remaining part. This makes the coastal zone to be at risk of diverse pollutants with impacts on ecological systems and human health.
- Along the Mediterranean coastal zone there are numerous sites that present a high risk associated with eutrophication of coastal waters due to nutrient inputs from land. This has adverse consequences on coastal ecosystems and, also, it may have local significant socio-economic impacts due to its impact on aquaculture, fishing and coastal tourism. In the future, it is expected that the risk along the Mediterranean coasts will increase following the expected increase in their occurrence and the increasing use of the coastal zone.
- The presence of areas of high concentration of plastics along the Mediterranean coastal zone represents a high risk for marine biodiversity and human health due to the ingestion and accumulation by marine fishes.
- Synergistic interactions between climate change impacts and emerging pollutants in the coastal environment will become more frequent (*medium confidence*) due to multiple stressors from both natural and anthropogenic sources.

Biological risks

- The Mediterranean coastal zone is subjected to a high risk associated with invasive non-indigenous species that produce different ecological and socio-economic impacts through their interaction with native species, which significantly affect native biodiversity. In addition, there is strong evidence that most of the services provided by Mediterranean marine ecosystems are affected by invasive non-indigenous species, being those related to food provision the most impacted ones (*high confidence*).

Impacts on the Economic System

- Coastal tourism along the Mediterranean is likely to be affected by climate change due to a decrease in climate comfortability, especially during the summer season, although spring and autumn will improve their climate attractiveness (*medium confidence*). In addition to this, sun-and-beach tourism will be negatively affected by the decrease in beach carrying capacity due to SLR-induced beach erosion. This will result in decreases of substantial revenue for the coastal communities, and consequently declines in GDPs of the region countries.

- Agriculture production in Mediterranean coastal zones will be negatively affected by climate change due to the expected decline in water resources, soil degradation and increase in salinity. This will directly affect food security.
- There is a high agreement that Mediterranean fisheries are overexploited and the majority of the stocks are declining. In addition to the current influence of excessive fishing, pollution and non-indigenous species, future projections show significant regional changes in fish abundance and distribution, so the majority of the stocks are declining in biomass, leading to shrinking fish stocks by quantity and by economic value and the emergence of non-indigenous species. This represents a financial and technical challenge for many artisanal fishermen, who dominate coastal fisheries.
- Climate change exacerbates challenges of water and energy securities through increasing temperatures, as well as decreasing precipitation and enhanced droughts.
- The risk for coastal infrastructures along the Mediterranean associated with climate change in general, and SLR in particular is mainly related to the decrease in their functionality mainly associated to increased coastal flooding and overtopping. In the absence of adaptation, although under low-medium SLR scenarios the expected change in risk is low, there will be a significant change in risk for Mediterranean ports by 2100 under the RCP8.5 scenario, from medium or low risk to very high or high (*medium confidence*). Although an increase in risk associated with decreased functionality of coastal protection infrastructure due to SLR is expected (*high confidence*), its significance will depend on its specific local configurations.

Impacts on the Human System

- The risk for coastal infrastructures along the Mediterranean associated with climate change in general, and SLR in particular is mainly related to the decrease in their functionality mainly associated to increased A large part of the existing UNESCO cultural World Heritage Sites (WHS) in the low elevation coastal zone of the Mediterranean are currently at risk to erosion and coastal flooding (*medium confidence*), with an expected increase in flood and erosion risk that will reach 50% and 13% higher values respectively by 2100 under a high-end SLR scenario (unlikely). In addition to this, the built heritage is likely to be affected by climate change through slow cumulative deterioration processes. Thus, there will be an increase in the risk of decohesion and fracturing of porous building materials.
- The occurrence of natural disasters and environmental degradation linked to pollution have multiple direct and indirect impacts on the health and well-being of coastal populations along the Mediterranean basin. In the absence of adaptation, their impacts are expected to increase in the near future due to the expected increase in the hazardous conditions due to climate change and the increase of coastal population.

Impacts on the natural system

- Mediterranean coastal wetlands have significantly declined during the 20th century due to a combination of erosion, extreme events, salt-water intrusion, and mainly human-induced pressures like expansion of irrigated agriculture and urban development. They will be significantly affected by future changes in precipitation (*high agreement*, *medium evidence),* although with a high spatial variability. SLR-induced hazards will lead to the loss of coastal wetlands (*high agreement*, *robust evidence*), being locally important in areas where existing rigid inland boundaries limit their potential of horizontal migration.

- SLR-induced erosion along the Mediterranean coast will induce a decline in ecosystem services provided by coastal habitats due to their degradation and, eventually, disappearance as erosion progresses (*high confidence*). For the northern Mediterranean coast, a decline in services of about 5% with respect to current conditions by 2100 under RCP8.5 has been estimated (*medium confidence*), presenting a high spatial variability, being the eastern Mediterranean, the area concentrating the largest estimated declines in ecosystem services.
- Any changes in sediment supply, industrial development, and urban processes will enhance the vulnerability of the coastal sandy beaches, saltmarshes, and mangrove forests to sea level rise. In addition, mangroves are experiencing compound threats due to ocean warming, sea level rise, eutrophication, and the low-oxygen zones formed as a climate change consequence. This risk is escalating to be very high by the end of this century (AR6, Chapter 3).

3.1 Introduction

The Mediterranean basin is generally characterised by a narrow and highly populated coastal area. In the second half of the 20th century, the Mediterranean population has doubled from 240 million to 480 million (UNEP 2016) and the human pressure on the coasts is further amplified by the increased international tourism. The Mediterranean coastal zone is thus characterised by an increased pressure from human activities, but also subject to future global environmental change being the Mediterranean area considered a hotspot of current climate change (Guiot and Cramer 2016). This may result in high sea-level rise rates compared to global averages, leading to significant losses in the environmental, cultural and economic values of Mediterranean coasts (Vacchi et al. 2021).

Mediterranean Sea-level rise will lead to more frequent flooding of low-lying coastal areas through storm surges, waves extremes and, in minor terms, through higher tides (See *Section 2.2.4*). Robust knowledge on current and future coastal risks enables Mediterranean policymakers to anticipate impacts that could be triggered by these multiple effects of climate change.

The assessment of impact and vulnerability is required in the framework of Integrated Coastal Zone Management (ICZM) Protocol of the Barcelona Convention (UNEP/MAP/PAP 2008). The integration of information from various fields including physical, ecological and socio-economic disciplines is a prerequisite for any coastal impact assessment and for the planning of appropriate future interventions along the Mediterranean shores (Wolff et al. 2018).

Due to the high natural, cultural and socio-economic values that might be threatened or lost in the Mediterranean coastal zones, several efforts have been made by the scientific community to produce future climate drivers including sea level scenarios (See *Chapter 2*) which may control the magnitude of problems that different Mediterranean coastal areas may have to face, as well as possible solutions.

3.2 Main risks in the coastal zone

3.2.1 Coastal risks – general

The Mediterranean can be considered a region with a high coastal risk due to the combination of multiple hazards such as erosion, flooding, pollution and biological hazards (e.g., Sánchez-Arcilla et al. 2011; Sarkar et al. 2022), a highly susceptible coast and an increasing exposure due to urban development (e.g., Wolff et al. 2020), a high concentration of coastal dependent economic sectors such as tourism (Plan Bleu 2016) and valuable ecosystem services (Liquete et al. 2016).

Due to this, multi-hazard risk assessments become an important tool for understanding and mitigating their potential impacts. However, due to the large diversity in risk components along the Mediterranean coast, most of the existing risk assessments are local (e.g., Torresan et al. 2012), or they analyze single hazards and some consequences (e.g., Reimann et al. 2018). Thus, most of studies covering large areas in the Mediterranean evaluated the coastal vulnerability instead of the coastal risk, that is the potential of the coastal system to be harmed by the considered hazards (e.g., Snoussi et al. 2009; Torresan et al. 2012; Hereher, 2015). One of the few examples of multi-risk assessment at the Mediterranean scale is due to Satta et al. (2017) who using an index approach to characterize hazards, vulnerability and exposure. Their analysis focuses on risks associated to erosion and flooding induced by different drivers and results are given in a 5-class qualitative scale from extremely high to extremely low risk. Obtained results characterize the Mediterranean coast with a heterogeneous spatial distribution of the risk, in form of hotspots, mostly controlled by the diversity in values at exposure and vulnerability (e.g., coastal geomorphology) (**Figure 3.1**).

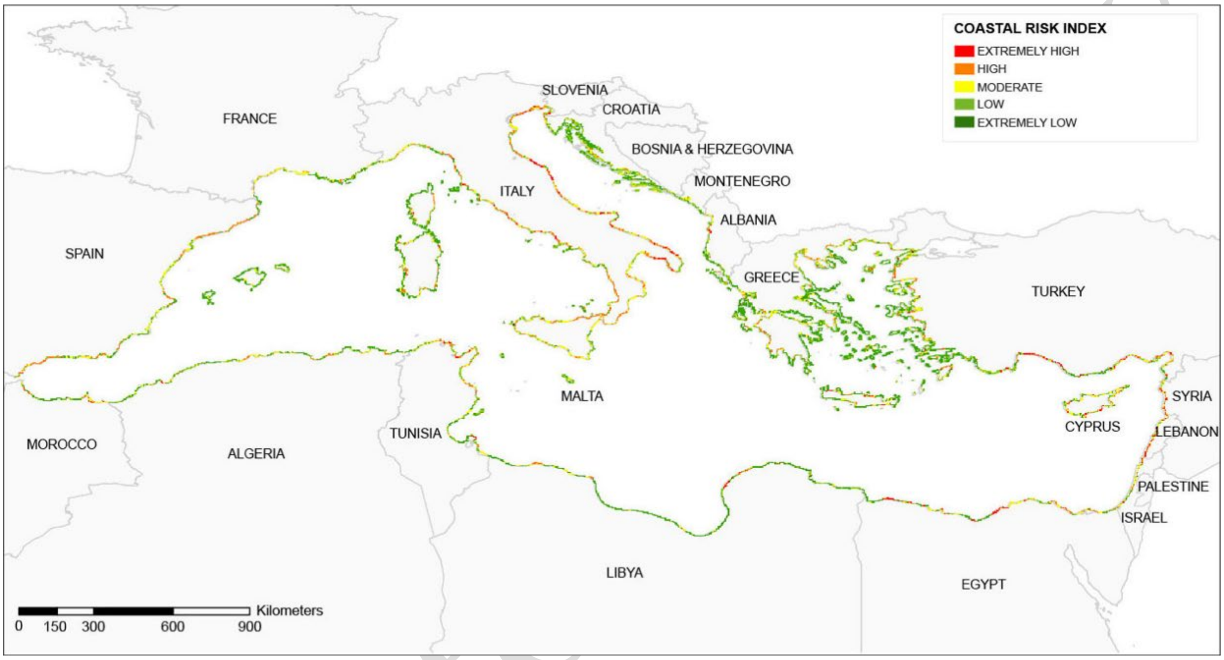

Figure 3.1 | Coastal Risk Index map of the Mediterranean (Satta et al. 2017).

3.2.2 Coastal erosion risks

One of the most common coastal risks is that induced by shoreline erosion, which currently affects a large extent of the world's sandy coasts (Luijendik et al. 2018; Mentaschi et al. 2018) and may be exacerbated by climate change (e.g., Nicholls and Cazenave 2020), threatening the survival of many sandy beaches (Vousdoukas et al. 2020) and affecting the functions they provide (Defeo et al. 2009; Roebeling et al. 2013; MedECC 2020).

Coastal erosion can be simply defined as the loss of a volume of sediment along a coastal stretch over a given time. The drivers and factors that control and determine coastal erosion, which have already been introduced in the previous Chapter 2, interact along the coast and operate at different timescales, such that to adequately characterise erosion requires doing so at multiple scales (e.g., Ballesteros et al. 2018a; Vousdoukas et al. 2020).

When analysing future erosion-induced risks, one of the points to be considered is that, even in the absence of climate change, many beaches along the Mediterranean are currently retreating and will significantly narrow and, eventually, disappear by the end of the century. Decadal-scale shoreline behaviour under current conditions in the basin has been characterised by Luijendik et al. (2018) and Mentaschi et al. (2018) and by EMODnet for the European Mediterranean (EMODnet, 2021) by analysing satellite images and aerial photographs. In this context, Vousdoukas et al. (2020) using the data from Luijendik et al. (2018) and Mentaschi et al. (2018) obtained for the entire basin a median shoreline retreat[1] of –17 m by 2100, with *very likely* values between –32 m and –1 m. These values presented a large spatial variability, although existing regional-scale analyses highlight the relevance of shoreline erosion along the basin. Thus, Jiménez and Valdemoro (2019) estimated that about 67% of the sandy shoreline of the Catalan coast (northwestern Mediterranean, Spain) is eroding at an average erosion rate of –1.6 m yr^{-1}, whereas the regional average shoreline evolution is around –0.4 m yr^{-1}. Similarly, Pranzini (2018) based on data from Tavolo Nazionale sull'Erosione Costiera (MATTM-Regionni, 2018) reported that about 50% of Italian sandy beaches are currently experiencing erosion in spite of the implementation of coastal protection projects. In the southern Mediterranean coast, Amrouni et al. (2019) estimated that about 70% of the sandy beaches along the Hammamet Gulf (Tunisia) are persistently eroding at an average rate exceeding –0.5 m yr^{-1}.

Current erosion hotspots[2] are mainly located in river mouth areas and coastal stretches around harbors and other coastal infrastructures. In the first case, river mouth areas are a direct consequence of one of the main terrestrial drivers affecting coastal stability, the decrease in river sediment supplies as a result of human-induced modifications of river basins (e.g., Syvitski et al. 2005). Thus, about 75% of the deltaic coastlines in the Mediterranean are retreating (Besset et al. 2019), and they comprise areas with the largest local erosion rates along the Mediterranean coastline such as Cap Tortosa at the Ebro delta, Spain (35 m yr^{-1} from 1957 to 2013; Ramírez-Cuesta et al. 2016); areas near the mouth of the Petit Rhône, France (10 m yr^{-1} from 1960 to 2000; Sabatier and Suanez, 2003) the Medjerda delta, Tunisia, (up to 42 m yr^{-1}, from 1972 to 2013; Louati et al. 2014); Moulouya delta, Morocco (up tp 10 m yr^{-1}, from 1958 to 2006; Mouzouri and Irzi, 2011); Ombrone delta, Italy (10 m yr^{-1} up to 2013–16; Mammí et al. 2019) and Damietta promontory at the Nile delta, Egypt (42 m yr^{-1}, 1972–1990; Dewidar and Frihy, 2010; before the implementation of coastal stabilisation works). In the second case, stretches in the surrounding of harbours and marinas are the result of the modification of littoral dynamics by existing coastal infrastructures. Examples of such hotspots associated with large infrastructures are found at the ports of Tangier, Morocco (Sedrati and Anthony 2007) and Valencia, Spain, (Pardo-Pascual and Sanjaume 2019), or with the existence of several marinas along coastal regions such as in Tuscany, Italy (Anfuso et al. 2011); in Catalonia, Spain (Jiménez and Valdemoro 2019); and Greece (Tsoukala et al. 2015).

Future changes in decadal-scale shoreline erosion will be controlled by the projected changes in corresponding drivers. With respect to the contribution of waves, as mentioned in Chapter 2, existing projections under different scenarios predict for the Mediterranean a slight decrease in significant wave height and in storminess. This would imply that, in the worst case, the magnitude of littoral dynamics along the Mediterranean will tend to decrease slightly. However, there are some regional studies such as Casas-Prat and Sierra (2014) for the Catalan coast, which have estimated more significant changes in wave direction than in the wave height. This discrepancy in the contribution of wave drivers will introduce significant uncertainty in the projection of coastal dynamics, as it does not depend on one, but on a set of wave parameters, which may lead to opposite changes in sediment transport. In this sense, the expected changes in wave height and wave direction may lead to opposite changes in longshore sediment transport and have to be estimated locally (Casas-Prat et al. 2016).

With respect to the contribution of riverine sediment supplies, existing estimations of average sediment delivery for 21st climate warming scenarios predict an increase by 11–16% (Moragoda and Cohen 2020), while for deltas, projected changes predict mean and maximum declines of 38%

[1] These values were estimated by extrapolating obtained shoreline evolution rates from satellite images during 2 decades to the end of the century without including SLR or any additional changes in drivers.

[2] Erosion hotspots are coastal locations where erosion rates are significantly higher than in surrounding areas

and 83% respectively between 1990–2019 and 2070–2099 (Dunn et al. 2019). The final contribution will be the result of the balance between climate-induced changes and human-modifications in river basins (Syvitski et al. 2022).

Finally, the estimated increase of human occupation and use of the coastal zone along the Mediterranean for the next decades (e.g., see *Section 2.6*) will likely contribute to alter littoral dynamics patterns and reduce the existing accommodation space along the coast due to the construction of coastal infrastructures. However, this will depend on the level of existing artificialization along the coast, as the already highly developed areas have shown attenuation in the increase of armoring as observed in the Mediterranean coast of Andalusia (Spain) (Manno et al. 2016).

Superimposed on current evolution rates, sandy shorelines will be directly affected by relative sea level rise (RSLR), inducing additional shoreline retreat, which, unlike current conditions, will be generalised although with spatial variations depending on local RSLR values, existing geomorphology and local sediment balance (Nicholls and Cazenave, 2010; Ranasinghe, 2016). While RSLR-induced erosion is a certain hazard, its assessment is still an open issue. Thus, although the equilibrium-based Bruun's rule is the most used method (e.g., Le Cozannet et al. 2014), there is a disagreement about its validity (e.g., Cooper and Pilkey 2004) and alternative models have been proposed (e.g., Ranashinge et al. 2012). In spite of this, all models have been hardly validated and they have an inherent uncertainty (e.g., Le Cozannet et al. 2016) and, even more, their application also involve different sources of uncertainties (Toimil et al. 2020) and, as a consequence, no universally accepted model exists.

At the Mediterranean basin scale, Vousdoukas et al (2020), using a modified version of the Bruun's rule estimated a median long-term shoreline retreat due to SLR of –17.5 m ±[–27.7 –8.8] and –23 m ±[–36.3 –11.1] for the year 2050 under the IPCC AR5 RCP4.5 and RCP8.5 scenarios respectively (*very likely*), increasing to –40 m ±[–65.1 –20.1] and –65 m ±[–115.0 –31.3] respectively by the year 2100 (*very likely*). Expected RSLR-induced retreats present a spatial variability driven by local increases in RSLR, with expected larger values in subsiding areas such as major deltas, and areas with milder slope shore faces. As an example, Sharaan and Udo (2020) estimated an increase in SLR-induced shoreline retreats along the Nile delta by 66% when compared to those calculated for RCP8.5. In addition to this global and consistent assessment, there are numerous local and regional assessments using different RSLR scenarios and erosion models. Among them, it is worth highlighting few ones for high-end scenarios that are relevant from a risk management perspective (Hinkel et al. 2015) such as that of Jiménez et al. (2017) for Catalonia (Spain) and that of Thiéblemont et al. (2019) for the entire European coastline. These assessments predict much larger shoreline retreats, proportional to the increase in SLR considered in such scenarios.

The combination of beach evolution rates at the different scales and their projection for the next century will result in a progressive and cumulative shoreline retreat along the entire Mediterranean coastline with the exception of those areas where local sediment budget determines the accumulation of sediment to compensate for such erosion. This combined with current high rates of urbanisation along the Mediterranean coastline (Wolff et al. 2020), as well as projected urban development (Wolff et al. 2020), limit accommodation space along the coast, favouring the appearance of coastal squeeze leading to generalised beach narrowing and, consequently, an increased probability of beach disappearance in the absence of adaptation measures (e.g., Jiménez et al. 2017; Vousdoukas et al. 2020).

One of the direct consequences of coastal erosion is the loss of ecosystem services (ES) provided by beaches, since habitats occupying the coastal zone may be affected, degraded and, eventually, disappear as erosion progresses, especially due to coastal squeeze. In the Mediterranean basin, the most comprehensive existing study is that of Paprotny et al (2021) who evaluated the effect of coastal erosion for ecosystem services in the European coast (just the north Mediterranean margin) for RCP4.5 and RCP8.5 scenarios. They estimated a decline in services of about 5% with respect to current conditions by 2100 under RCP8.5. The estimated risk presented a high spatial variability reflecting the variability on habitat distribution and magnitude of induced erosion, being the eastern Mediterranean, the area concentrating the largest estimated declines in ecosystem services along the European Mediterranean coast.

In addition to these chronic erosion processes, the impact of storms on Mediterranean sedimentary coasts can cause large episodic erosional events, with shoreline retreats of the order of 10's of metres occurring over the duration of the event (up to few days) (e.g., Adriatic coast (Ferrarin et al. 2020); Algier (Amarouche et al. 2020); NW Mediterranean (Jiménez et al. 2018). The magnitude of the induced erosion will depend on the one hand, on the incident storm properties (waves and surge). As in general, the most severe wave storm conditions are found in the Western Mediterranean (e.g., Sartini et al. 2017), this would be the area most susceptible to experiencing larger storm-induced impacts. However, the real beach erosion will not only depend on the storm magnitude but also in the protection capacity provided by beaches and dunes (i.e., local geomorphology) in such a way that storms need to exceed a given threshold to produce a significant impact on the coast (e.g., Armaroli et al. 2012 for critical thresholds in the North Adriatic Italian coast; Gervais et al. 2012 in the Gulf of Lion French coast). The stochastic nature of the storms and their large spatial variability along the basin, the dependence on the geomorphology of the coast at the moment of the impact, and the variety of existing models with different predictive capabilities make that few assessments are available at the Mediterranean basin scale. In this regard, Vousdoukas et al (2020) predicted a basin-averaged storm-induced shoreline retreat of about 4 m for a return period of 100 years without significant climate change-induced variation by the end of the century. This value was obtained using a simplified approach to optimise calculations along the entire world coastline and, as average value, it underestimates registered retreat recorded along the Mediterranean coastline, and also existing predictions in the area which amounts up to about 20 m or even larger for similar return periods (e.g., Armaroli and Duo 2018; Jiménez et al. 2018).

Future changes in the magnitude of the storm-induced erosion will be controlled by projected changes in wave storms along the Mediterranean. Although, as mentioned in *Chapter 2*, existing projections for different scenarios do not predict any significant increase in wave height, some new analysis of wave buoy records and hindcasts have detected an increasing trend of recorded maximum significant wave height during the last 40 years in the W Mediterranean, with some records during the last years (Amarouche et al. 2022). Finally, it has to be considered that associated impacts to erosion are largely controlled by the existing geomorphology, and as described above medium- and long-term erosion will largely dominate future coastline evolution along the basin. Thus, even in the case that storm climate will not change during the next decades, decreasing beach widths (increasing geomorphic vulnerability) and increasing development of the coastal zone (increasing exposure) will lead to increasing erosion risk along the Mediterranean basin. This has already been detected during the last decades of the 20th century and beginning of the 21st century in the north-western Mediterranean (Jiménez et al. 2012).

3.2.3 Flood risks in the coastal zone

Flooding in the coastal zone can be simply defined as the situation in which dry land is submerged by water. Similar to the case of erosion, the drivers and factors that control and determine flooding, which have already been introduced in the previous chapter, are of different origin and operate at different timescales, such that to characterise flooding requires doing so at different scales.

Flash floods

As mentioned in *Chapter 2* (see also MedECC 2020), one of the drivers of flooding in the Mediterranean coastal zone is the terrestrial origin, and it is mainly caused by short-term (episodic) high-precipitation events inducing flash floods events (Llasat et al. 2010; Gaume et al, 2016). These, usually, disastrous floods are more frequent in the Mediterranean coastal areas than other European regions, due to local climate and topographic conditions on the one hand, and the high population and urban settlements in flood-prone coastal areas (Gaume et al. 2016). Floods events have increased since 1981 in regions of Italy, France and Spain (Llasat et al. 2013). This positive and significant trend of 2.5 floods per decade would be mainly due to extraordinary floods, usually associated with local heavy rainfall events in ungauged catchments usually surrounded by very populated villages, as a consequence of an increase in vulnerability and exposure, despite improved coping capacities (Llasat et al. 2021). The work of Tramblay et al. (2019) shows that with the same large-scale climatic drivers (in terms of temperature, evapotranspiration and precipitation), the flood trends in the basins can differ, even for neighbouring basins, as a consequence of other factors like topography, soil and land cover combinations. The analysis by Blöschl et al. (2019) shows a decreasing trend for the Mediterranean region in medium and large basins for the period 1960–2010, mainly due to a decrease in precipitation and increased evaporation (see also *Section 2.2.2*). This trend is consistent with the climate projections shown by Alfieri et al. (2015), that agree on a 30% reduction in annual precipitation in southern European countries, particularly in the Iberian Peninsula, Greece and southern Italy, with the consequent decrease in average streamflow.

In the future, disastrous flash floods will likely become more frequent and/or intense due to climate change and the growth of urban areas (*medium confidence*). In some Mediterranean regions the contribution of convective precipitation to total one has increased in the last 20 years, which points to a major hazard of heavy rainfalls (Llasat et al. 2021). This fact is aligned with the increase in heavy precipitation projected by Tramblay and Somot (2018) in the northern Mediterranean region for the middle of the century, and by Cortès et al. (2019) for the Eastern part of the Iberian Peninsula. These authors have projected an increase in the precipitation recorded by events exceeding 40 mm per day, threshold associated with potential flash floods. If this precipitation increase is combined with different socioeconomic scenarios it is found an increase in the probability of an event with significant economic damage occurring.

Coastal floods

At the same scale but of marine origin, the impact of coastal storms with high waves and/or storm surges will cause the temporary inundation of the coastal zone when water level at the shoreline exceeds the elevation of the coast. This hazard, usually accompanied and enhanced by beach and dune erosion in sedimentary coasts, is frequent along the entire Mediterranean coastline, with their magnitude depending on the local values of the total water level, the local level of protection (provided by the beach/dune in natural areas and structures in urbanised coasts) and the extension of the flood plains. As a consequence, although there are different studies providing global or continental-scale extreme sea levels for both present and future climate, existing attempts for mapping flood prone areas at such scale have not been validated (Paprotny et al. 2019), and they need to be done at local level to have a reliable estimation of the risk (e.g., Perini et al. 2016). It has to be considered that under the European Directive on Floods, most European Mediterranean countries have produced risk maps for coastal inundation associated with different return periods (https://ec.europa.eu/environment/water/flood_risk/links.htm).

Scicchitano et al (2021) analysed the coastal flooding in Sicily under common storms and Medicanes and they found that, although they are apparently similar drivers, flooding due to Medicanes was significantly greater than those estimated for common seasonal storms, due to the higher induced storm surge. Toomey et al (2022) characterise coastal hazards under Medicanes and found that the highest induced waves are generated in the central and the southwest part of the western Mediterranean, whereas the highest surges are mainly found in the Adriatic Sea.

Compound events

One of the intrinsic characteristics of flooding in coastal areas is that it can be induced by different climatic drivers such as storm surge, run-up, rainfall, and/or river flow, which are often interconnected (Berghuijs, 2019), and may produce what is usually called as compound flooding. Depending on their typology, they can induce an impact that is amplified relative to the impacts from those same events occurring separately, or they can accumulate impacts at spatially distant locations (Zscheischler et al. 2020). They have been identified in historical information on past damaging floods in Europe, especially in Italy and France (Paprotny et al. 2018), and the recent impact of very extreme Gloria storm in January 2020 along the Spanish Mediterranean coast has drastically showed their integrated impact (e.g., Amores et al. 2020; Canals and Miranda 2020). From the risk perspective, these events are very relevant, because they can significantly increase the intensity and/or the spatial and temporal extension of the impact (and damage) and it may overwhelm the capability of emergency-response services since they have to respond to a large number of emergency situations throughout the region at the same time, and/or they have to maintain the level of response during a relatively long period.

When analysing these events, different drivers can be considered to contribute to the compound flooding. Bevacqua et al (2019) analysed compound flooding by considering events to be compounded by heavy rainfall rates and high-water levels due to surge and astronomical tides. They found that the highest probability under present climate is mainly concentrated along the Mediterranean coast, with the regions of the Gulf of Valencia (Spain), the northwestern Algeria, the Gulf of Lion (France), southeastern Italy, the northwest Aegean coast, southern Türkiye, and the Levante region having return periods shorter than 6 year to experience compound flooding. A similar result was obtained by Camus et al (2021) who analysed compound events of pluvial, fluvial and oceanographic drivers along the European coasts and found the northern Mediterranean coast to be a hotspot of compound flooding potential. On the other hand, Couasnon et al (2020) analyse compound flooding by combining river discharges and storm surges and they found that the Mediterranean Sea was one of the areas where there was not a clear pattern in the co-occurrence of these drivers.

As an example, at a smaller scale, Sanuy et al (2021) analysed the occurrence of compound events heavy rainfall and storm waves in the NW Mediterranean coast (Catalonia, Spain), and they found that the area has a high probability of experiencing compound extreme events (an average of 3 events per year), although showing significant variations in event characteristics along the territory even the relatively small size (about 500 km of coast).

With respect to the future evolution of these events, existing analyses do not show conclusive results. Thus, according to the work of Bevacqua et al (2019), climate models do not agree about the direction of future changes in the probability of compound flooding over much of the Mediterranean coast. In this sense, Prapotny et al (2020) analysed the performance of different models to predict these events in Europe and found considerable regional differences in strength of the dependence in surge-precipitation and surge-discharge pairs. Thus, the models reproduce those dependencies reasonably well in northwestern Europe, but less successfully in the southern part.

SLR-induced inundation

Finally, flooding at the long-term scale, will be driven by climate change that can cause a gradual permanent inundation of the coastal zone due to sea level rise and, also may enhance storm-induced flooding.

To assess the extension and risk associated with SLR-induced inundation, the first element to be characterised is the local magnitude of relative sea level rise (RSLR) along the coastal zone. In the

Mediterranean, there is an increasing availability of SLR flooding scenarios, notably for those sites which are particularly prone to the coupled effects of sea-level rise and negative vertical land motions such as the deltas and the coastal plains, which are the one concentrating the highest risks of permanent inundation (e.g., Snoussi et al. 2008; Aucelli et al. 2017; Antonioli et al. 2017; Vecchio et al. 2019; Lopez-Doriga and Jimenez 2020). These studies followed a variety of methodologies which are mainly based on the use of IPCC SLR scenarios (corrected for the local GIA contribution) coupled with the assessment of local subsidence which can be derived from Holocene data (e.g., millennial scale), from long tidal gauges (e.g., centennial scale), GPS or Insar data (e.g., decadal scale).

Furthermore, future sea-level scenarios should be considered reliable only if based on high-resolution topography derived from Lidar data. Digital Elevation Models (DEM) derived from Lidar surveys are now available for a large portion of the Mediterranean coasts and are often provided with 1 x 1 or 2 x 2 m cell width. These data have a general mean vertical resolution of about 10 to 20 cm (Anzidei et al. 2021; Rizzo et al. 2022). Any scenario based on topographic data with lower vertical accuracy should be disregarded because the associated topographic error may represent more than the 30% and more than 50% of the expected flooding in the 2100 RCP8.5 in the RCP2.5 scenarios, respectively.

With respect to the used flooding technique, most the Mediterranean Sea-level scenarios are based on a classical “bathtub” approach in which areas below the expected sea-level elevation and hydraulically connected to the sea are delineated as being flooded (e.g., Di Paola et al. 2021). This methodology is considered suitable for urban, armoured, rocky, and passive coasts characterised by moderate wave action and reduced sediment supply. However, “bathtub” flooding scenarios approach may be less accurate for active sedimentary coast where future sea-level rise have more dynamic effects than inundation alone (Fitzgerald et al. 2008; López-Dóriga and Jiménez, 2020). In this morphological context, a wide range of processes driving coastal evolution is expected to occur which may counteract the incoming sea-level rise. The dynamic responses of shorelines were presently seldom included in most of the Mediterranean assessments of future sea-level scenarios.

Another important challenge in the definition of future flooding scenarios is to define a clear relationship between the inundated area and the resulting damage (López-Dóriga and Jiménez, 2020). A typical approach is to consider the loss of function/habitat occupying the inundated area even if this often overestimates damage, especially from an environmental standpoint, as the resilience of natural areas is not always considered (Lentz et al. 2016). Presently, determining the physical and ecological responses of coastal habitats to future change remains a difficult task (López-Dóriga and Jiménez, 2020). There is thus a growing need to integrate dynamic interactions between physical and ecological factors to better predict the impact scenarios of sea-level rise on low-lying coasts.

SLR-enhanced floods under storms

In addition to this, it is expected that climate change and, SLR in particular, will increase extreme total water level at the shoreline (including wave runup and storm surge) and the associated flood risk (e.g., Vousdouskas et al. 2018a; Kirezci et al. 2020; Almar et al. 2021). In practical terms, SLR will induce a decrease in return periods for given total water levels, which implies an increase in the probability of occurrence of flood events (they will be more frequent) or, in an alternative manner, the total water level associated with a given probability of occurrence will be higher.

Almar et al. (2021) have estimated the current variation in temporary coastal flooding by assessing the annual number of overtopping hours[3] from 1993 to 2015. They found an increasing trend in

[3] Defined as the number of hours during which the extreme coastal water level exceeds the maximum coastal elevation

most parts of the world coastline, being the Southern Mediterranean one of the areas presenting the largest increase. This was associated with the fact that it is a region with a small variability in extreme coastal water levels, and even small increases in regional sea level can have a large impact on overtopping. Under the RCP8.5 scenario, these authors estimated that the globally aggregated annual overtopping hours by the end of the 21st century is projected to be up to 50 times larger compared to present-day, and more regions are projected to become exposed to coastal overtopping.

In an independent study, Kirezci et al (2020) estimated that in the absence of coastal protection or adaptation, and assuming mean RCP8.5 SLR scenario, there will be an increase of 48% of the world's land area, 52% of the global population and 46% of global assets at risk of flooding by 2100 with respect to the current situation. The estimated increase in flood risk along the European coast has been associated with rising extreme water levels and increasing socioeconomic development of the coastal zone (Vousdoukas et al. 2018b), being climate change the main driver of the future rise in coastal flood losses. With respect to the magnitude of estimated extreme total water levels under SLR by 2100, it has to be considered that the Mediterranean basin is the area with the lowest predicted total water level, being the North Adriatic in Italy and the Gulf of Gabes in Tunisia, the areas with the highest water levels.

3.2.4 Tsunamis and meteotsunamis in the Mediterranean

Tsunamis

Tsunamis are unpredictable and infrequent but potentially large impact natural disasters. Underwater and/or coastal earthquakes, volcanic eruptions, as well as landslide processes are sources that can generate a tsunami (Papadopoulos 2014). Due to active geodynamic processes, the seismicity in the Mediterranean region is high. The tsunami activity, although not so frequent, seriously threatens the communities along the coastal zones of the Mediterranean basin (e.g., CIESM 2011). Tsunami sources in the Mediterranean Sea are situated in the near-field domain, that is the travel times of first tsunami wave arrivals do not exceed half an hour or so. This feature is extremely critical from the point of view of tsunami risk mitigation.

Tsunamis in the Mediterranean Sea have often caused severe damage and loss of lives. Although they are less frequent than those of the Pacific or Indian oceans, some of them are well known from historical accounts, such as the M > 8, 365 AD and 1303 earthquakes near Crete and the M > 7, 1222 earthquake near Cyprus in the Eastern Mediterranean. In the Western Mediterranean basin, a devastating tsunami hit the coasts of Sicily and Calabria in 1908 following M > 7 earthquake in the Messina Straits (Lorito et al. 2008). Some examples in the last years are the M6.8 Boumerdès 2003 (Algeria) event affecting Balearic Islands, the M6.7 Kos-Bodrum 2017 (Greece-Türkiye) Aegean Sea and M7.0 Samos, Aegean Sea 2020 (Greece-Türkiye). According to (Papadopoulos 2014) most of the events and the most intense in the Mediterranean has occurred in the eastern Mediterranean basin, which means a tsunami recurrence of 93 years. The Hellenic Arc is a major geotectonic structure dominating the east Mediterranean basin and producing large earthquakes and tsunamis. Respective rates in the Western Mediterranean basin are 227 years; the Marmara Sea and the Black Sea are 500 and 1250 years.

A great deal of effort has been put into data collection in the Mediterranean to collect data for the tsunami monitoring operations from novel observational techniques and sensors. These include deep-sea sensors including ocean bottom seismometers, tidal gauges, tsunameters, smart cables, and possibly DAS (Distributed Acoustic Sensing) technology, and high-precision coastal real-time GNSS (Global Navigation Satellite Systems) for a better characterization of the tsunami source (see Babeyko et al. 2022). These instruments have been essential to reduce the uncertainty related to the tsunami itself and tsunami source and to which is complementary to the uncertainty exploration that has been achieved by tsunami simulations.

Although climate change will not imply any change in the probability of occurrence of a tectonically-induced hazard such as tsunamis, it will indirectly increase their potential impact and risk, due to increased water levels under SLR that would potentially increase the inundated surface (e.g., Li et al. 2018). Existing preliminary assessments of such effects in the Eastern Mediterranean found that risks would increase due to SLR and that this driver needs to be incorporated into future tsunami risk assessments (Yavuz et al. 2020).

Meteotsunamis

Meteotsunamis are those tsunamis induced by atmospheric processes. 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.

Hot spots in the Mediterranean where meteotsunamis are observed to occur regularly and where severe damages have been reported are mainly the Balearic Islands (more particularly Ciutadella harbour in Menorca Island) (Monserrat et al. 1991a) and the Adriatic Sea (Vela Luka, Stari Grad in Croatia, etc.) (Hodžić 1979) but also the Strait of Sicily (Šepić et al. 2018a), the Maltese Islands (Drago 2009), and some sites in the Black Sea (Šepić et al. 2018b; Vilibić et al. 2020).

Despite their undoubtedly interest for the Mediterranean coasts, meteotsunami hazard has only been assessed in the Mediterranean for the Adriatic and Balearic sites (e.g., Vilibić et al. 2008; Orlić et al. 2010; Šepić et al. 2016; Ličer et al. 2017), but not for other regions. And risk assessment has not been formally carried out for any of the Mediterranean hotspots, even for those, which are periodically affected by meteotsunamis.

3.2.5 Scarcity of appropriate quality water resources

Freshwater resources risks; salt water intrusion

The magnitude of the risk for coastal water resources is the result of the balance between water demands and existing resources. The recent historical climatology in the Mediterranean coastal areas explains the existence of important water demands in these areas, which tend to have a high seasonality (Niavis et al. 2021). These demands are due to the existence of large populations, as well as intensive and highly productive agricultural and/or important industrial activities (Renau-Pruñonosa et al. 2016). The very important Mediterranean tourism (the Mediterranean zone is the largest tourist destination in the world; UNTWO 2018) and irrigated agriculture produce clear demand peaks during summer and will even grow in the future, stressing water availability in these periods (Toth et al. 2018). Therefore, the supply of demands in these coastal areas with significant urban, agricultural and/or industrial development, and scarce water resources is a challenging issue (Zouahri et al. 2015), especially during droughts and, even more critically, during the summer due to tourism demand, which might be exacerbated in the future due to climate change (Tramblay et al. 2020). In accordance with global warming scenarios, in addition to an increase of irrigation demands, we expect an increment in population, particularly in the coastal areas of eastern and southern Mediterranean countries leading to higher water demands and further deterioration of water quality (Cramer et al. 2018).

In many areas along the Mediterranean coastal zone, surface water resources are scarce and/or intermittent, which forces supply demands partly or totally by using groundwater resources (Sola et al. 2013). Preserving water quality in these water bodies, which also influence water availability for different water uses, is a challenging issue. In addition to the traditional water quality risks existing in inland systems (e.g., nitrate and pesticide pollution, urban and/or industrial discharges, emerging contaminants, etc) we also have to deal with salinity issues due to seawater intrusion (Custodio 2017). Considering that aquifers are the main source of water supply in many Mediterranean countries (Leduc et al. 2017), there has been a certain degree of over pumping, especially during summer and drought periods. It has led to salinization processes with seawater progressing into coastal aquifers (Rosenthal et al. 1992). In general, the Mediterranean areas with higher risks arising from extreme hydrological events (droughts and floods) are located in the coastal areas (MEDECC, 2020). The most frequent and severe droughts are usually observed near the coast (Gomez-Gomez et al. 2022). Many aquifers of the EU Mediterranean coastline in Italy, Türkiye and Spain have suffered historically saltwater intrusion (**Figure 3.2a**) (EEA 2009). For example, in

Spain, 56 of the 95 identified coastal groundwater bodies have been affected by seawater intrusion processes (Custodio 2017). The intrusion is also very relevant across Greece, where it is estimated that the total surface area of aquifers impacted by seawater intrusion is about 1500 km^2 (Daskalaki and Voudouris 2008). The Mediterranean North Africa coast is also extensively affected by seawater intrusion (**Figure 3.2b**). Significant saltwater intrusion is observed in the Nile Delta in Egypt (Sefelnasr and Sherif 2014), in Mauritania coastal area (Friedel and Finn 2008), and in Jeffara plain, Libya (CEDARE 2014).

Regarding the future evolution of freshwater resources, the degradation and reduction of the availability of conventional freshwater resources for the different uses is expected, especially in the southern and eastern Mediterranean (*high confidence*). The increase in water demand and in the frequency and severity of droughts, the reduction of freshwater recharge, and the effect of sea level rise will lead to an increase in seawater intrusion in coastal aquifers (Pulido-Velazquez et al. 2018; Tramblay et al. 2020).

The unconventional water resources generated by desalination in the Middle East and North Africa Mediterranean will reduce the risk of water scarcity, but it will increase the risks of environmental impacts, especially on near-coastal marine ecosystems, the energy requirements and the associated CO_2 emissions (*high confidence*).

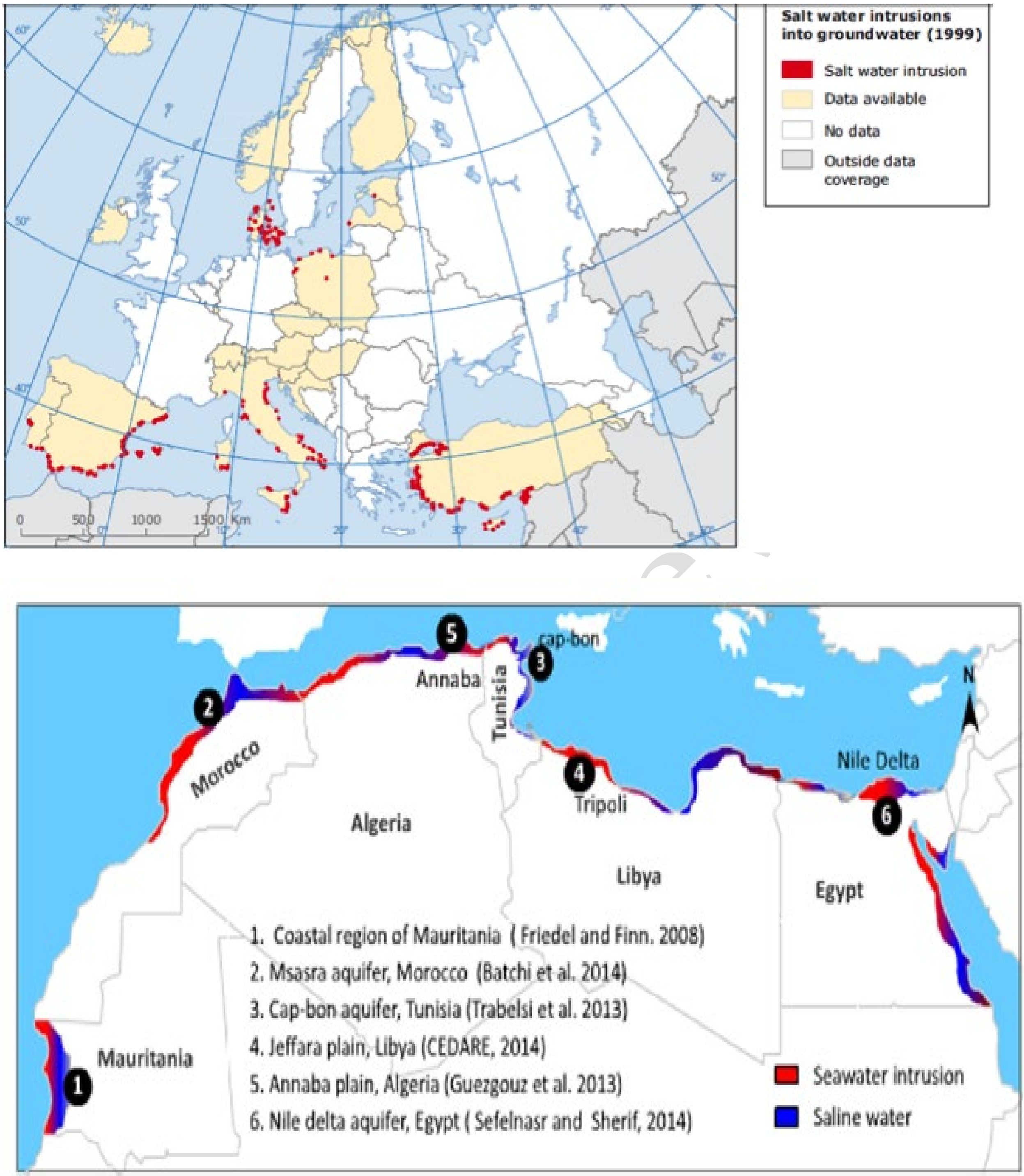

Figure 3.2 | a) Maps of historical saltwater intrusions into groundwater in Europe in 1999 (EEA, 2009); b) Maps of SeaWater intrusion in North Africa (Agoubi, 2021)

3.2.6 Coastal pollution risks

Pollution in coastal waters

The littoralisation[4] together with heavy urbanization along the Mediterranean coastal zone have increased water quality risks. Changing consumption patterns have led to a dramatic increase in the amount of solid waste, as well as wastewater discharged into coastal waters (Geyer et al. 2017). 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 and pesticides/herbicides as well as storm water runoff from urban areas carrying toxic pollutants from hydrocarbon residues. The share of land-based pollution is 80% in the Mediterranean according to MED POL[5] (Inniss et al. 2016; UNEP/MAP 2022). Ship-originated pollution and air pollution make up the remaining 20%. Maritime accidents can be the source of very serious pollution which affects the marine and coastal ecosystem for several years and have severe impact on human and environmental health which translates into significant economic losses (Ülker and Baltaoğlu 2018; Ülkeret al. 2022).

Consequently, coastal water quality is at risk of diverse pollutants. Marine pollutants are of a wide diversity comprising physical, chemical and biological origins that create harmful effects on ecological systems. These adverse impacts on the natural systems might be generated due to various anthropogenic activities that bring several substances/materials into the coastal waters. In case they exceed certain threshold values, these substances are very likely to become harmful and to present detrimental effects on the biological components of the coastal ecosystems (Beiras 2018). In addition to organic pollution, other pollutants of various origins exist, some of which are toxic and persistent like POPs, whose origins can be identified in recent years. Their threshold values are regulated by the Stockholm Convention (UNDP 2011), some others are micro-pollutants whose components are also of various origins (e.g., pharmaceuticals and personal care products (PPCPs), micro-plastics), which are emergent.

Accumulated pollution from various sources in coastal and bathing waters endangers human health as well as the health of coastal ecosystems because the magnitude of anthropogenic impacts has been higher in coastal waters compared to offshore waters with increasing pressure due to climate change, overfishing and pollution as prevailing pressures altogether (Díaz et al. 2019; Halpern et al. 2008)

An overview of nutrients, metals, emergent pollutants, persistent organic pollutants and major environmental changes due to climate change and their impacts on coastal ecosystems will help understand the synergistic effects of climate change and marine pollution. Researches have revealed that the interplay between environmental effects and impact caused by multiple stressors both from natural and anthropogenic sources result in synergistic effects. Recent findings suggest that synergisms are predominant under multiple stressors because increased stressor intensity is likely to overcome compensatory mechanisms (Harley et al. 2006; Crain et al. 2008; IPCC 2014; Przelawski et al. 2015; Gunderson et al. 2016; Lange and Marshall 2017)

Nutrients

Eutrophication caused by excessive land-based nutrient inputs has affected many areas in the coastal zone as shown on **Figure 3.3**. Coastal eutrophication which generates due to the sea water enrichment with mainly nitrogen and phosphorus has significantly increased within the last past decades in the semi-enclosed parts of the Mediterranean, in particular (Danovaro et al. 2009; Cabral

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[4] Littoralisation is defined by the United Nations in CCD Annex IV for the Northern Mediterranean as the process of concentration of population, settlements along with economic activities in coastal areas (UN, 2022)

[5] Programme for the Assessment and Control of Marine Pollution in the Mediterranean (MED POL)

et al. 2019). This phenomenon has a widespread impact on the ecosystem by promoting various negative effects including hypoxia or anoxia, episodes of massive mucilage formation, harmful algal blooms (HABs), and acidification.

The most detrimental negative effect is usually hypoxia, which represents concentrations of dissolved oxygen lower than 2 mg L^{-1}, the threshold value for living organisms (Crain et al. 2008; Howarth 2008). Similarly, another harmful effect may be generated by toxic HABs which may cause human illness and even mortality and they have socio-economic impacts related to toxicity of harvested fish and shellfish, loss of aesthetic value of coastal ecosystems, and reduced bathing water quality impacting tourism activities of the coastal zones on the Mediterranean Basin. Coastal eutrophication is of medium or important significance in 13 Mediterranean countries (Table 3.4 in MedECC 2020).

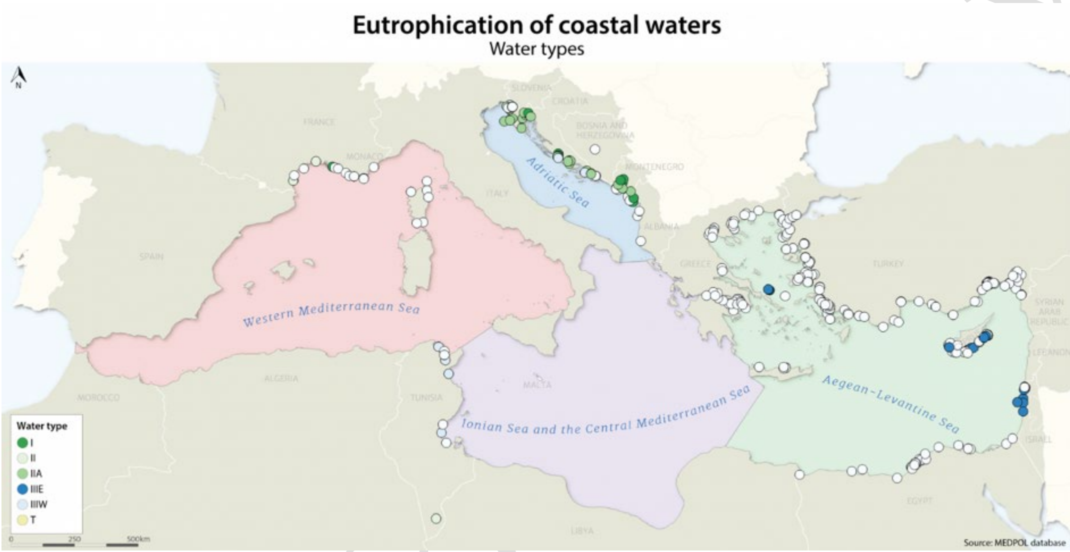

Figure 3.3 | Eutrophication in the Mediterranean (UNEP/MAP 2017)

Mucilage

Mucilage is a dense and highly viscous substance made up of extracellular polysaccharides produced and secreted by the overgrowth of various aquatic species. Rising ocean temperatures, as well as human-induced stressors like inadequate treatment levels and overfishing, are common causes of such algal blooms. Although mucilage is a harmless organic material structurally, studies have indicated that mucilage is home to various harmful microorganisms including pathogenic species (e.g., bacteria and viruses) (Del Negro et al. 2005; Precali et al. 2005; Danovaro et al. 2009).

The highly productive and shallow Adriatic Sea within the Mediterranean Sea is reported as the most severely affected area by massive marine mucilage (Danovaro et al. 2009). The frequency of the mucilage phenomenon is indicated to have increased significantly during the last decades. Mucilage adversely affects the seawater and makes it unsuitable for bathing due to the adherence of this mucus-like product on the bathers' skin. Marine mucilage may float on the sea surface and then in the water column for a long-life span of 2 to 3 months and once settled on the benthos in the form of large aggregates, it coats the sediment, causing hypoxic and/or anoxic conditions (Precali et al. 2005). Consequently, suffocation of benthic organisms poses serious economic damage to tourism and fisheries (Rinaldi et al. 1995).

As an example, the semi-enclosed Marmara Sea whose bottom water is constituted with the Mediterranean Sea more saline waters was severely threatened by a mucilage outbreak in May 2021 (**Figure 3.4**). The sea surface was covered with thick layers of foam on beaches and harbours that threatened marine life, tourism, fisheries, maritime traffic and the economy due to the fact that fishing was not practised for a while for the prevention of possible sea-borne disease and furthermore due to the reluctance by the consumers. Even though this was not the first mucilage phenomenon in the Marmara Sea and this was not region-specific, it was the worst, ever happened. The mucilage phenomenon attracts increasing attention as it severely impacts the overall ecology particularly benthic organisms (Savun-Hekimoğlu et al. 2021).

Figure 3.4 | Mucilage in the Marmara Sea (May 2021)

Metal pollution

Estuaries are repositories/sinks for historical metal contamination associated with metals' strong particle reactivity with sediments (e.g., Golden Horn estuary in Istanbul, Archeloos River estuary) (Ridgway and Shimmield, 2002; El-Amier et al. 2021; Zeki et al. 2021). Although biological processes need some metals that are essential for reactions, some others are not metabolised, but in both cases, high toxicity may occur even in small concentrations (Lu et al. 2018). Toxic effects of metal exposure include an increased energy demand, which impacts the metabolic structure and growth of the marine ecosystems (Ersan et al. 2011). The toxic effect of metals may also act as strong immunosuppression or cause impaired reproduction and/or development (Rainbow, 2002). Since trace metals are not degradable, they accumulate in marine organisms throughout food webs (Vareda et al. 2019). Mercury bioaccumulation in marine food webs is a representative example of this issue (Fonseca et al. 2019), given that it is shown that mercury exposure causes severe neurotoxic effects in marine fauna and humans (Depew et al. 2012; Karagas et al. 2012). Despite trace metal abatement measures in the marine environment have been enhanced in the last decades in parallel with the enforcement of the EU Directives, mercury pollution is acknowledged as an issue worldwide due to its persistence and most importantly its long-distance transport in the environment which may cause transboundary pollution.

Emerging Pollutants

Pharmaceuticals and personal care products (PPCPs)

Pharmaceutical residuals can be found in surface waters, coastal waters of heavily populated settlements and in drinking water samples in Europe (López-Serna et al. 2013; Chen et al. 2018; Yang et al. 2020). These substances present acute or chronic toxicity risk to aquatic organisms in coastal waters. In addition to their toxic effect, some of them are endocrine disruptors (EDCs) (Esplugas et al. 2007). Therefore, PPCPs exhibit hazardous effects due to their continuous discharge into the coastal waters via wastewater treatment plants which are unable to treat them by conventional processes. Environmental health concerns stem mainly from long-term exposure to these substances, whether they are persistent or not (Daughton and Ternes 1999; Korkmaz et al. 2022).

Few researchers have recently investigated the environmental risk assessment related to the existence of pharmaceuticals in coastal waters (Chaves et al. 2020; Navon et al. 2020; Sadutto et al. 2021; Yang et al. 2020; Dehm et al. 2021).

Microplastics

Several researchers carried out field surveys and assessed the threat posed by plastic pollution to the coastal and marine ecosystem of the Mediterranean (Jambeck et al. 2015; Geyer et al. 2017; Compa et al. 2019).

With the high production and consumption of plastics worldwide, the marine environment, in particular, has been suffering at all levels, (i.e., coastal waters, off-shore, sediment) from the plastic dispersion and deposition. Similarly, the Mediterranean marine diversity is at high risk of plastic exposure (Compa et al. 2019). In addition to its continuous release into the environment, plastics disintegrate into smaller pieces and disperse into nature undergoing different processes, mainly physical and chemical. Some of the principal sources of marine litter are coastal zones and river emissions, in particular (Löhr et al. 2017). High concentration of plastics composed of small items may have considerable environmental, health, and economic impacts (Pedrotti et al. 2016). The worst impacted regions are the coastal areas, which are hotspots for plastic ingestion, and the Mediterranean coastal area is no exception (Compa et al. 2019). Plastic ingestion affects the gastrointestinal system of marine species ranking from invertebrates to mammals, including demersal and pelagic ecosystems (Taylor et al. 2016). Plastic exposure analyses put forward that marine species with larger home ranges are more at risk of exposure due to longer distances while local species are more likely to be exposed to plastic closer to their home range areas (Compa et al. 2019).

Fossi et al. (2017) suggested that a risk assessment of plastic pollution for the entire Mediterranean basin will help gather data sets to better understand the species under exposure and/or threat and determine hotspot risk locations. It should be noted that the existing threat is quite difficult to assess due to the different ecological requirements of multiple species. Compa et al. (2019) identified hotspots under the risk of plastic ingestion across multiple taxa in the Mediterranean Sea, highlighting that coastal species are at higher risk of ingesting plastic in the marine environment than open-sea species as shown on **Figure 3.5**. However, the impact of plastic pollution on different seabirds and sea turtles put forward that the risks are not limited within the coastal areas but may expand further to the high sea locations (Schuyler et al. 2016).

Atmospheric pollution

Atmospheric emissions that settle at sea are a source of pollution, which impact the oceans by the acidification phenomenon. Ocean acidification has severe impacts on a wide diversity of marine organisms such as corals, planktonic organisms and calcifying structure's organisms resulting in their degradation and mortality. Various studies in the Mediterranean have been started by research institutions, particularly in the eastern Mediterranean (the Levant Sea) in order to monitor the evolution of acidification and assess its impact on marine food webs (Lacoue-Labarthe et al. 2016).

Oil spill pollution

Oil spill from refinery and maritime accidents can be the source of very serious oil pollution which affects the marine and coastal ecosystem for several years and have severe impact on human and environmental health which translates into significant economic losses (Ülker and Baltaoğlu, 2018; Ülker et al. 2022).

Persistent Organic Pollution (POPs)

POPs may travel long distances in the aquatic environment and may accumulate in the sediment because they are highly particle-associated due to their hydrophobic properties. Contaminated sediments represent a significant threat to the associated biota and also for other organisms via the marine web food chain (e.g., demersal fish and marine birds). Furthermore, as a result of sea level rise and sea water intrusion in the coastal aquifers, POPs which exist in coastal waters may contaminate coastal aquifers, impairing the quality of fresh water resources.

Across the Mediterranean Basin, ocean and inland pollution are transboundary, ubiquitous, diverse and increasing in both quantity and in the number of pollutants, due to demographic pressure, enhanced industrial and agricultural activities, and climate change (*high confidence*) (see MedECC 2020 Section 2.3.1).

Persistent organic pollutants (POPs) create a severe concern on transboundary pollution as their transmission can be long distances away from their sources since these are not biodegradable in water but in fatty acids of living organisms and can, thus, enter the web food chain (MedECC, 2020). Thus, the synergistic effects of climate change and coastal water pollution may result in transboundary water pollution affecting even terrestrial coastal systems like coastal aquifer and coastal ecosystems located at long range from the origin of pollution.

The synergistic effects of climate change and coastal pollution are shown on **Figure 3.6** (Cabral et al. 2019).

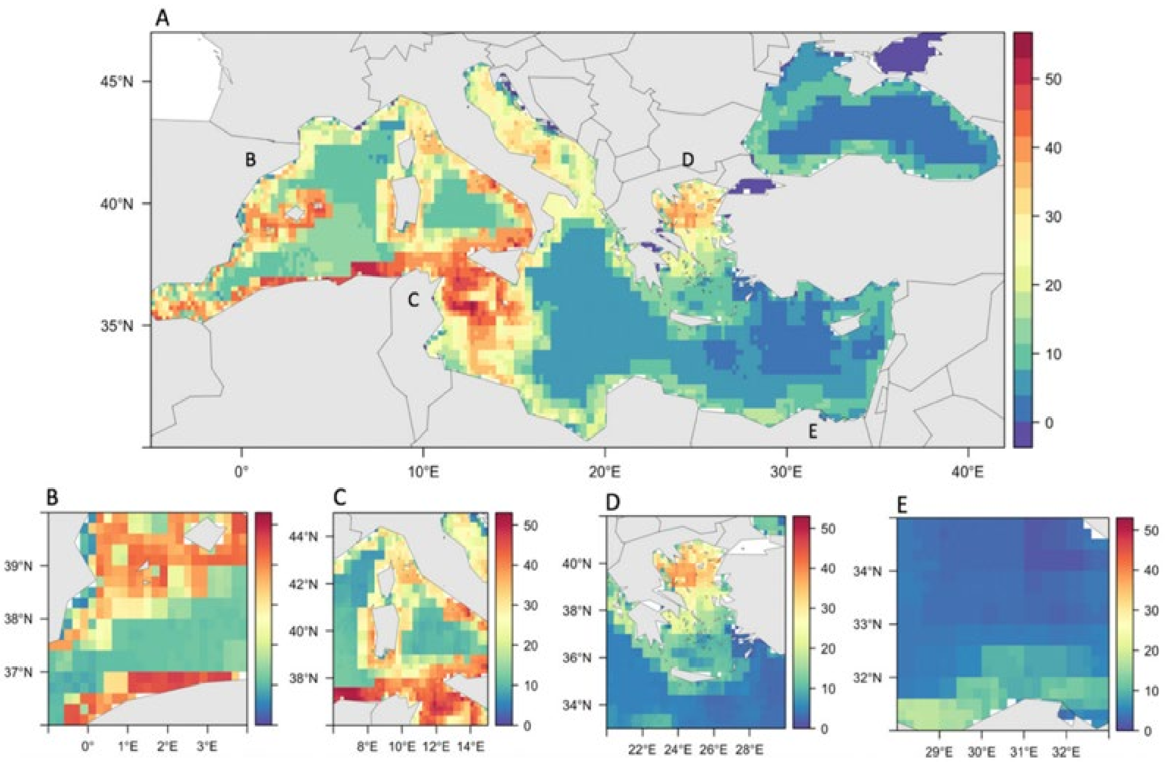

Figure 3.5 | Overall risk of predicted plastic ingestion across the Mediterranean Sea for the 84 species modelled based on the best-fit GAM model incorporating motility, habitat, body size and class (A). Red indicates high-risk areas and blue areas of low-risk of plastic ingestion in the marine diversity. Hotspot areas of plastic ingestion risk of the marine diversity for: B) coastal areas of the Strait of Gibraltar and surrounding countries, C) the Pelagos Sanctuary and the northern coast of Africa, D) Aegean Sea and E) the northern coastal areas of the south-eastern Mediterranean Sea (Compa et al. 2019).

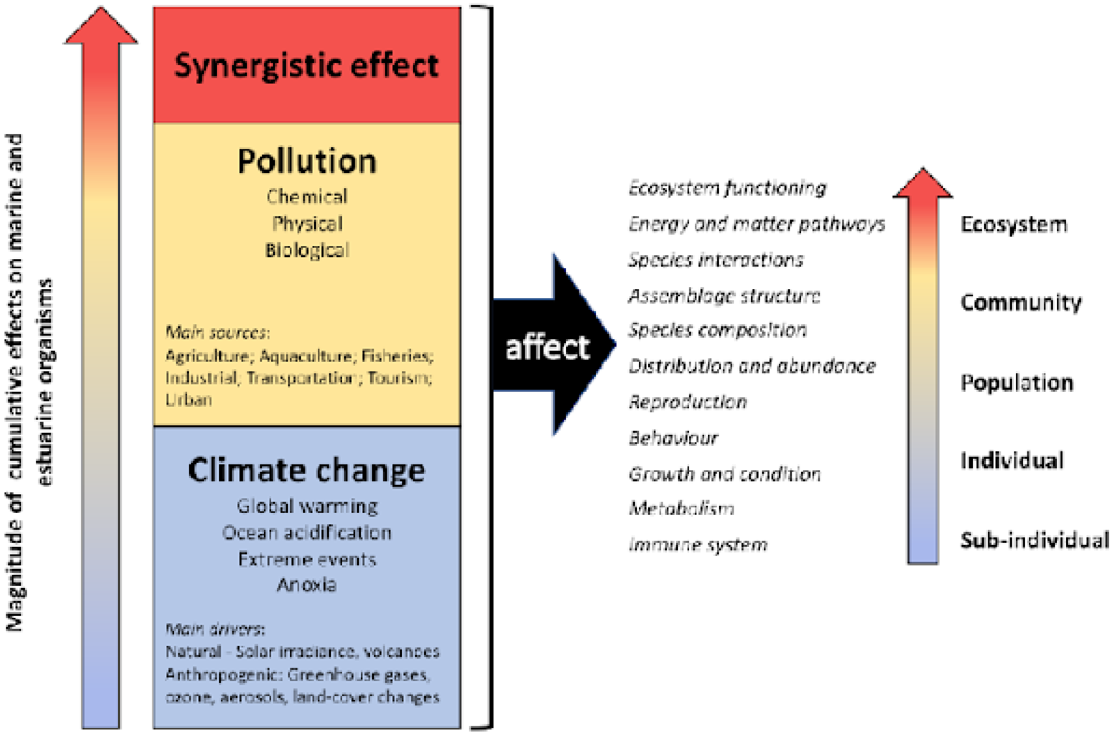

Figure 3.6 | Synergistic effect of climate change and coastal pollution (Cabral et al. 2019)

[Placeholder]: The drafting of a subsection on water pollution risks in Mediterranean ports (as hotspot) is under consideration.

3.2.7 Risks of biological origin

Non-indigenous species

Regardless of their origin, the non-indigenous species are producing a variety of ecological and socio-economic impacts on the Mediterranean (Katsanevakis et al. 2014, Azzurro et al. 2022a). Most of them have been reported to affect more than one native species through a variety of mechanisms, such as predation (Gueroun et al. 2020, Prado et al. 2022), competition for resources (Caiola and Sostoa 2005, Marras et al. 2015), food web shifts (Finenko et al. 2003, Piscart et al. 2011) and vectors of pathogens or parasites (Roy et al. 2017, Peyton et al. 2019). In many cases, they also impacted keystone species or species of high conservation value (Caiola and Sostoa 2005, Prado et al. 2022). There are also many examples of non-indigenous species that modify ecosystem processes or wider ecosystem functions (Pancucci-Papadopoulou et al. 2012, Rilov et al. 2019). The extreme of such examples are those species that behave as ecosystem engineers, that is to say that modify, create or define habitats by altering their physical or chemical properties (Wallentinus and Nyberg 2007, Berke 2010).

In addition to the mentioned impacts on native biodiversity, invasive non-indigenous species also negatively affect coastal ecosystem services (Katsanevakis et al. 2014, Galil et al. 2017). There is strong evidence that most of the services provided by Mediterranean marine ecosystems are affected by them. The most affected services are the ones related to food provision but regulating and maintenance and cultural benefits are also impacted (**Table 3.1**).

Table 3.1 | List, type and description of marine ecosystem services adapted from Liquete et al. (2013).

PROVISIONAL SERVICES
Food: Provision of biomass (fishery and aquaculture) from the marine environment for human consumption.
REGULATING AND MAINTENANCE SERVICES
Water purification: Biochemical and physicochemical processes involved in the removal of wastes and pollutants from the aquatic environment.
Air quality: Regulation of air pollutant concentrations in the lower atmosphere.
Coastal protection: Natural protection of the coastal zone against inundation and erosion from waves, storms or sea level rise.
Climate regulation: Carbon sequestration.
Weather regulation: Influence on the local weather conditions (e.g., influence of coastal vegetation on air moisture and temperature).
Ocean nourishment: Natural cycling processes leading to the availability of nutrients and organic matter.
Lifecycle maintenance: Maintenance of key habitats that act as nurseries, spawning areas or migratory routes.
Biological regulation: Biological control of pests and invasive species.
CULTURAL SERVICES
Symbolic and aesthetic values: Exaltation of senses and emotions by seascapes, habitats or species.
Recreation and tourism: Opportunities for relaxation and entertainment (e.g., bathing, sunbathing, snorkelling, SCUBA diving, sailing, recreational fishing, whale watching).
Cognitive effects: Inspiration for arts and applications, material for research and education, information and awareness.

As already mentioned, and according to Katsanevakis et al. (2014), food provision was the ecosystem service that was impacted by the highest number of invasive non-indigenous species. The most cited examples of this impact type are the negative effect on fisheries resources (Prado et al. 2020, Kleitou et al. 2022). Following food provision, the ecosystem services that were negatively affected by most species were ocean nourishment (Godoy et al. 2010, Fuentes-Grünewald et al. 2013) cultural services in general (Klein and Verlaque 2008, Gravili 2020), and lifecycle maintenance (Salomidi et al. 2012, Katsanevakis et al. 2014). Harmful algal blooms caused by non-native species negatively impact food and water provision (see Marampouti et al. 2021). This type of impact on water resources can be exacerbated by climate change effects that will cause water shortages in some Mediterranean regions and, therefore, drinking water would rely on desalination. Native phanerogam species and bivalves potentially deliver coastal protection services, which are quite important under climate change scenarios of sea level rise and increase of magnitude and frequency of storm surges (Ibáñez and Caiola 2022). Invasive non-indigenous species affecting these indigenous species (Prado et al. 2020, 2022, Houngnandan et al. 2022) can, thus, potentially impact coastal protection services. Although to a lesser extent, there is evidence of invasive non-indigenous species impacts on materials for non-food purposes, water purification (see Salomidi et al. 2012). Mediterranean seagrasses are potential carbon sinks and therefore provide weather regulation services. Thus, invasive aquatic vegetation that competes with native seagrasses can potentially negatively impact this ecosystem service (Silva et al. 2009). No or negligible impacts were documented for air quality regulation and biological regulation services (Katsanevakis et al. 2014)

3.3 Impacts on the Socio-Economic system

3.3.1 Impacts on tourism

There is high agreement with robust evidence that climate change and its induced hazards impact tourism (Perch-Nielsen et al. 2010; Seetanah and Fauzel, 2019; Arabadzhyan et al. 2021) (*high confidence*). The Mediterranean region, the destination of almost 200 million tourists, is known as one of the most vulnerable regions to climate change (Stratigea et al. 2017; Cannas, 2018, Rick et al. 2020). The region is expected to face heatwaves, a significant decrease in rainfall, an increase in periods of drought, and an increase in sea levels (Galeotti 2020), all of which will *likely* influence the tourism industry in the region (Perry 2000; Scott et al. 2008; Anfuso and Nachite 2011; Dogru et al. 2016; Rizzetto 2020). It is predicted that the Mediterranean region will become "too hot" for tourist's comfort in the summer (Amelung and Viner 2006; Scott et al. 2008; Rutty and Scott 2010; Arabadzhyan et al. 2021). For example, the suitability of Southern Europe for tourists will shrink in the summer holiday months but improve between October and April (Perch-Nielsen et al. 2010). Climate change *likely* changes the destinations and seasonal distribution of tourism (Ciscar et al. 2011; Amengual et al. 2014; Koutroulis et al. 2018), tourist activities (Caldeira and Kastenholz 2018), and alter tourism flows as well (Scott et al. 2008; Magnan et al. 2013;).

In a survey-based study, Moreno (2010) showed that although the climate is a strong attribute from Mediterranean tourists' point of view, heat waves will *more likely than not* have the least climate change impact compared to rainfall. Amelung and Viner (2006) predicted spatial and temporal changes in climatic attractiveness, which would affect the sustainability of tourism development, making spring and autumn more desirable (*high confidence*).

There are various case studies on the impacts of climate change on tourism in the Mediterranean region. El-Masry et al. (2022) argued that climate change will cause devaluation of coastal tourist destinations and thus a decline in revenues for the El Hammam–EL Alamein region in Egypt. They predict a downward shift in the region in terms of tourism climatic suitability in the future. Abo El Nile (2017), through survey research for MENA countries, showed the impact of climate change on beach tourism in the region and discussed the need to anticipate changes and to adapt. Katircioglu, et. al., (2019) presented positive climate change influences on foreign tourist flows to Malta and Cyprus. Enríquez and Bujosa Bestard (2020) found the negative impact of climate-induced environmental change on tourists' attractions by measuring economic impacts on the coast of Mallorca (Spain). Vrontisi et al. (2022) also found harmful impacts of climate change on the tourism sector in southern European islands. Hall and Ram (2017) analysed the negative influences of climate change on coastal tourism in Israel. In summary, there is *high confidence* that climate change influences tourism and consequently affects the Mediterranean economies.

One of the most direct impacts of climate change on coastal tourism along the Mediterranean basin is *likely* the decrease in the beach recreational carrying capacity as a consequence of the projected increase in shoreline retreat (see *Section 3.2.2*). This is due to the decrease of available beach surface for recreational purposes due to beach narrowing (in those areas with a rigid landward boundary limiting the accommodation space as tourist beach areas use to be) with the corresponding increase of the density of users during the first stages, which will be followed by the decrease in beach users as density exceeds saturation values beach (Valdemoro and Jiménez 2006; Rodella et al. 2017). This risk is *very likely* to occur in highly-developed areas with beaches of intensive use such as the Spanish, Italian, France and Greece coasts. Thus, López-Doriga et al. (2019) estimated that the beaches along the Catalan coast (Spain, north-western Mediterranean) will potentially experience in 2050, in the absence of adaptation, an overall decrease of 19% of BCC under current conditions, increasing to 36% under RCP8.5. For coastal counties highly specialised in tourism, this represented a potential decline in their GDP of between 18% and 26% under RCP8.5 by the end of the century (Garola et al. 2022).

3.3.2 Impacts on food security and agriculture

Climate change is one of the critical environmental challenges for production systems in the Mediterranean area (Capone et al. 2020; Hossain et al. 2020) and is expected to threaten agriculture (Aguilera et al. 2020; Kavadia et al. 2020). It is expected to reduce food production in the region (Grasso and Feola 2012; Galeotti, 2020) and negatively impact the biodiversity of agriculture (Palatnik and Lourenço Dias Nunes 2015), fisheries and aquaculture (see *Section 3.3.3*). Crop yields for winter and spring are expected to decline because of climate change, especially in the southern Mediterranean (Galeotti, 2020). In addition, climate change will influence the growth cycles of crops and could result in significant limitations in this regard (Funes et al. 2021). Sub-regionally, North African countries are more vulnerable to climate change in agriculture than Northern Mediterranean countries (Atay 2015).

As introduced before, climate change will negatively impact the availability of water resources (see *Chapter 3.2.4*). Since agriculture is the leading water consumer in the Mediterranean region (Daccache et al. 2014; Pool et al. 2021), this expected decrease in water resources will affect agriculture (García-Garizábal et al. 2014; Papadopoulou et al. 2016) with significant detrimental ramifications on the productivity of crops (del Pozo et al. 2019). Due to climate change, the Mediterranean area may need more water for irrigation, between 4 and 18% more (Fader et al. 2016). Brouziyne et al. (2018) predicted a 26.4% decrease in basin water yield and a 44.7% decrease in crops produced by rainfall by 2050. Reduction of spring rainfall due to climate change thus would result in a decrease of rain-fed crop production. In addition, climate change could harmfully impact intensive dairy farming in terms of milk production and quality, and cattle mortality (Dono et al. 2016).

Another impact of climate change on agriculture is through soil degradation—climate change threatens the natural capital of soils (Ferreira et al. 2022). Kourgialas et al. (2016) predicted considerable soil erosion with a mean annual loss of 4.85 t ha^{-1} yr^{-1}. This study highlighted that soil loss would increase by 32.44% and 50.77% in 2030 and 2050, respectively, compared to current conditions (Kourgialas et al. 2016).

Various case studies focus on the impacts of climate change on agriculture and food production. For Egypt, Fawaz and Soliman (2016) predicted that by the year 2030, the cultivated area would be reduced to about 0.949 and crop area by 1.406 million acres (just about 8.22% and 6.25% of the existing area). Consequently, the value of Egyptian agriculture production would decrease by about 6.19 billion US dollars (Fawaz and Soliman 2016). Salinity in the soil in the Nile Delta coast would rapidly increase and organic matter content will decrease, especially during the summer season (El-Nahry and Doluschitz 2010). In Türkiye, the yield of crops would decrease at a growing rate due to climate change (Bozoglu et al. 2019). In Andalucia (Southern Spain), climate change could cause a 95% reduction in sunflower crops by 2100 in addition to a decline in wheat production (Abd-Elmabod et al. 2020). Bosello and Eboli (2013) predicted an average production loss of 0.5% for the agricultural sector of southern and eastern Mediterranean countries.

In addition, there are studies focused on the detrimental impact of climate change on particular products in parts of the region, including orchards (del Pozo et al. 2019), grapevines (Ferrise et al. 2016; del Pozo et al. 2019), viticulture (Santillán et al. 2020), wheat (Ferrise et al. 2011; Dixit et al. 2018; Zampieri et al. 2020; Reyes et al. 2021), durum wheat (Dettori et al. 2017), barley yield (Cammarano et al. 2019), olives (Ponti et al. 2014; Fraga et al. 2020; Fraga et al. 2021; Rodrigo-

Comino et al. 2021;), and rice (Bregaglio et al. 2017) in the eastern Mediterranean and the Middle East (Constantinidou et al. 2016). For mushrooms, unlike the results for the other products, Karavani et al. (2018) predicted higher fungal productivity for 2016–2100 compared to current mushroom yields. Moreover, Atay (2015) anticipated a 1.1% rise in wheat yields, 0.36%, and 0.67% decline in maize yields, and 2.0% and 2.8% increase in potato yields due to a 1% increase in temperature in two groups of countries in the Mediterranean region.

Reduced crop yields combined with population growth and urbanization, increasing competition for water and changing lifestyles including diets, are also expected to impact food security in the MENA (Middle East and North Africa) region (Jobbins and Henley 2015). A typology of impacts of coastal risks, mostly due to climate change, on agriculture and food security can be proposed. First, direct impact of coastal risks (from climate change) on agriculture: loss of agricultural productivity in coastal areas (but not necessarily due to location of crops and livestock near to coasts); loss of ecosystem services associated with food provision (Mehvar et al. 2018), depletion of natural resources especially nutrients and water. Regarding the latter, this is due to salt intrusion because of sea level rise but also of over-pumping from groundwater resources (Galeotto 2020). For agroecosystems, salinization of soils may cause changes to the distribution of plants and animals, while seawater intrusion is expected to cause additional risks in coastal aquifers, with severe impacts on agricultural productivity (Ali et al., 2022).

Second, a direct impact on total agricultural output is due to land loss because of coastal erosion, and loss of some farm infrastructures (access roads, agricultural buildings, irrigation networks, etc.). For example, farmland may be converted to tourism-related areas because of coastal erosion (Luisetti et al. 2008), while in some cases farmland is lost (“coastal squeeze”) to wetlands that “retreat” onto agricultural land that are cannot no longer be cultivated because of submersion (Kuhfuss et al 2016). Erosion and salinisation are already harming soil contents and production capacity in the Mediterranean region, with previously fertile soil prone to desertification, and these factors of reduction of agricultural land are exacerbated by climate change (ARLEM 2021). As pointed out by FAO (2015), reduced livelihood options in the coastal regions will force occupational changes and may increase social pressures, because livelihood diversification as a means of risk transfer will be reduced (e.g., between farming and fishery).

Third, indirect impacts due to land use change because global trends connected or not to climate change will also affect agricultural activities in coastal areas. Moreover, water availability and quality in coastal areas will probably diminish due to saltwater intrusion driven by enhanced extraction and SLR, also because of increased water pollution from urban sprawl, tourism development and population growth (Hinkel et al. 2014). Population growth in coastal areas will mechanically increase demand for local food, with increased demand for irrigation water as a corollary, particularly in the coastal areas of eastern and southern Mediterranean countries (Cramer et al. 2018).

Local ecosystem-based and Nature-based solutions (e.g., conservation and revegetation projects, Integrated Coastal Area and River Basin Management) that may reduce the impacts of coastal risks on agriculture in the Mediterranean have been proposed in UNEP/MAP and Plan Bleu (2020). Joshi et al. (2016) estimate the economic impacts of SLR on regions including Africa and the Middle East, to conclude that economic impacts due to loss in cropland without protection are low (compared with loss of capital, change in labour supply and government expenditure on migration), and that the economic impact of SLR is affecting South-East Asia, Australia and New Zealand potentially the most. Note also that, given the limited share of total agricultural output of MENA countries (with the exception of Türkiye), coastal risks due to climate change in MENA region are not likely to have a strong impact on global markets for agricultural commodities (Chen et al. 2012).

Confidence level and knowledge gaps.

Research needs are particularly needed on a variety of dimensions of climate change in relation with agriculture and food security. First, more research is necessary on the impact of climate change for crops and products less present in the agricultural literature than orchards, grapevines, viticulture, wheat, barley, olives and rice in particular. Second, several issues could not be addressed due to lack of data, in particular the expected decrease in local water resources that will affect agriculture at the landscape (or small river basin) level. Uncertainty about the extent to which the Mediterranean area may need more water for irrigation may be reduced by collecting more comprehensive data on the extent of soil degradation (as climate change threatens the natural capital of soils). Moreover, uncertainty remains on the indirect impacts on coastal areas due to land use change, because changes at the global level (associated or not with climate change), will impact agriculture in these areas. Water availability, and water quality of the latter, will probably be reduced because of saltwater intrusion due to excess resource extraction and SLR, but also because of increased water pollution from urban expansion and population growth. However, more case studies on a larger set of contrasted settings in the Mediterranean region are necessary to obtain a more representative vision, which could provide guidance for policy design and to decision makers.

Finally, better knowledge of local expected impacts and data collection efforts, especially South and East of the Mediterranean region, are needed to provide a more effective plan for action, as the majority of scientific literature addresses coastal risks and agriculture in South Asian countries, the United States and Pacific Islands (Kumar et al. 2022) or for large world' regions not expliciting MENA (Bosello et al. 2007).

3.3.3 Impacts on fisheries and aquaculture

Biodiversity and functioning aquatic ecosystems act as a safety net, buffering us from massive changes affecting the very tissue of life and the civilizations we have been able to build during long times of relative stability. In addition to excessive fishing, the heaviest erosion is perpetuated by human-made climate change, such as global warming in combination with ocean acidification and lowered levels of dissolved oxygen, river and ocean pollution, increasing dead zones as a result of over-fertilization from runoff generated by industrial agriculture and untreated sewage, and massive influxes of invasive species (IPBES 2019). Changes in temperature, nutrient supply, mixing, light availability, pH, oxygen, and salinity are *very likely* expected to affect the ecological functions and, consequently, the sustainable harvests available from the ocean's biological communities (Cochrane et al. 2009; Brander 2010; Denman et al. 2011; Doney et al. 2012). Exposure of marine organisms to ocean acidification and oxygen depletion will vary regionally, and other anthropogenic impacts (e.g., eutrophication) may also contribute. The vulnerability of species to these changes varies considerably (Whitney et al. 2007; Feely et al. 2008; Vaquer-Sunyer and Duarte, 2008; Levin et al. 2009; Ries et al. 2009; Rabalais et al. 2010).

Mediterranean fisheries are extremely diverse because of the heterogeneity of the sea with respect to the number of species harvested, variety of fleets, hydrography, bathymetry and productivity (Barange et al. 2018) but also to the varying cultural, social and economic conditions across the Mediterranean coastline (Stergiou et al. 2016). Nearly 400 species of fish, crustacean, and molluscs are being exploited by numerous fishing gears and methods in the Mediterranean Sea, yielding over one million tonnes of catches according to official statistics (FAO 2022). Most gears and fisheries in the Mediterranean target a high number of species, while large monospecific stocks are generally lacking compared to the Atlantic Ocean (Lleonart and Maynou 2003). The dominant fisheries fleet segment in the Mediterranean and Black Sea regions is the small-scale segment, consisting of polyvalent vessels (i.e. using more than one type of gear) up to 12 m length, which makes up 80 percent of the total fleet and employs the highest number of fishers. In contrast, trawlers land the resources with the highest value and purse seiners have the highest landings by mass (FAO 2016).

Recent publications based on scientific surveys, stock assessments and catch data, generally agree that the Mediterranean fisheries are overexploited and the majority of the stocks are declining in biomass. According to a report based on the official stocks assessments, 85% of the assessed stocks have been reported as being exploited beyond the exploitation that produces the maximum sustainable yield (Colloca et al. 2013), while Cardinale and Scarcella (2017) maintain that all target species are being overexploited. Recently, using the catch-based method, the cumulative percentage of collapsed and overexploited stocks was reported to exceed 60% (Froese et al. 2018) with the exploitation pattern differing among the Mediterranean subareas (Tsikliras et al. 2015). Local reports also confirm the overexploitation of Mediterranean fisheries (e.g., Greek seas: Tsikliras et al. 2013; Ligurian Sea: Abella et al. 2010; Turkish seas: Demirel et al. 2020), which is often attributed to bad or inadequate management practices (Tsikliras 2014; Cardinale and Scarcella 2017). Finally, there is *high confidence* that the exploitation rate in the Mediterranean is steadily increasing and gear selectivity deteriorating; both conditions are *likely* leading to shrinking fish stocks (Vasilakopoulos et al. 2014).

Climate change is adversely affecting the range and quantity of species available (*high confidence*) and is leading to changes in fisheries and the emergence of non-indigenous species (*high confidence*). The progressive occurrence and establishment of warm-water species (Lloret et al. 2015) is likely expected to generate both positive and negative effects on fisheries (Hidalgo et al. 2018), especially on small scale fisheries because of their socio-economic and ecological sensitivity. Those generalised effects can be listed as i) increase of warm water species such as bluefish (*Pomatomus saltatrix*) and barracuda (*Sphyraena viridensis*) as examples of "Meridionalization in northern Mediterranean areas (*medium confidence*); ii) presence of Indo-Pacific species (Lessepsian migrants) in the Eastern Mediterranean (Boero et al. 2008) as evidences of "Tropicalization" (*high confidence*), and iii) extension of the distribution ranges of Mediterranean species and detection of non-indigenous species in the Black Sea called as "Mediterranization" (*low confidence*). There is *high confidence* that non-indigenous species compete with native species (e.g., rapa whelk – *Rapana venosa*; Demirel et al. 2021) or include highly damaging toxic species such as pufferfishes (e.g., silvercheeked toadfish – *Lagocephalus sceleratus*; Ünal and Göncüoglu Bodur 2017). Some studies have considered the impacts of climate change on species and stocks, including trout (climate change influences the largest, oldest trout through increased metabolic costs) (Ayllón et al. 2019); finfish aquaculture in Greece (Stavrakidis-Zachou et al. 2021); demersal fisheries (Aragão et al. 2022); shellfish (Martinez et al. 2018); endemic freshwater fishes (*Padogobius nigricans*, *Squalius lucumonis* and *Telestes muticellus*) in the Tiber River basin (Italy) (Carosi et al. 2019).

Future projections show that regional changes in fish abundance and their distribution will *likely* alter species richness, with an expected increase in overall richness by the mid-twenty-first century in the Eastern Mediterranean, and a decrease in the western region (Albouy et al. 2013). A *likely* decrease in connectivity between neighbouring ecosystems within the Mediterranean is expected because of a decrease in the size of the spawning areas and an increase in larval retention on smaller areas of the continental shelf. Fish often move between marine ecosystems making them difficult to track, count and assess (Sinclair and Valdirmarsson 2003). Each species has a unique reproductive strategy and behavioural, physiological, and energetic adaptations, which comprise their ecological niche. Hence, healthy fish populations ultimately depend on the collaborative success of their spawning (*very likely*) and reproductive seasons, as well as prey availability (*very likely*), especially in changing environments under climate change. It is *very likely* that status of fish stocks is threatened by damage to the marine environment, but there is yet limited evidence with medium agreement that pollution namely poor waste management and land-based pollutants, such as metallurgical wastewater discharges, chemical releases and plastic litter have an impact on the health of the marine environment and living marine resources. Furthermore, as a result of climate change, hazardous storms and natural disasters are also increasingly more common (*very likely*). Those have made pursuing the fish both financially and technically challenging for many small-scale fishers.

Aquaculture plays an important role in the Mediterranean economy (Cubillo et al. 2021). The average per capita consumption of seafood in the Mediterranean region is 16.5 kg per year, and aquaculture activities provide almost 25 percent of it (Rosa et al. 2012, 2014). Climate change is *likely* expected to have direct and indirect effects on the aquaculture sector (FAO 2020). There is a *virtually certain* connection between the temperature preferences of aquatic species and their oxygen demands (Barange et al. 2018; Pauly 2018). Specifically, the oxygen concentrations required to meet the maximum oxygen demand for organisms determines their temperature preference. However, exposure of fish to higher temperatures than they are adapted to leads to changes in their physiological responses and increase in stress levels (Bell et al. 2018). This situation is *likely* expected to particularly affect the stenothermic pole species located at high latitudes and have a low tolerance for temperature changes (Roessig et al. 2004). In the short term, although raising water temperature is *likely* expected to increase the forage availability and growth rates of organisms, these rates will decrease as temperatures continue to rise, as cultivated species have limited space to move (Crosier et al. 2008). Hence, optimal areas for aquaculture are expected to shift towards the poles. As a result of climate change, extreme weather events such as strong winds and waves may *likely* damage facilities such as cages and platforms used in shell and fin aquaculture, and may cause negative consequences such as losses of brood stocks and high damage to facilities. Possible flooding in flat coastal areas at sea level suitable for breeding brackish water species is also predicted (FAO 2020).

Final remarks

The socio-economic importance of fisheries and aquaculture in food security and economic development, as well as in generating employment and income, necessitate a proactive approach in the formulation of adaptation and mitigation policies regarding climate change aquaculture interactions. Raising awareness and understanding the perceptions of stakeholders about the impact of climate change on fisheries is an important pillar of the adaptation and/or mitigation policy development process.

Fisheries management is the state of managing fisheries sustainably in a way that ensures long-term and optimal resource use. To effectively manage fish stocks, various control measures exist that directly or indirectly limit catches. However, the diversity of multi-types of fishing gear and target species makes fisheries management applications even more complex. In the Mediterranean basin, which is more heavily affected by climate change than the global seas and human-induced pressures, intensive efforts are necessary to develop responsive fisheries management, for example, timely restriction on fishing effort and protection of spawning stocks by way of fishery closure for minimizing the amplified impacts of excessive fishing effort and environmental change. Continuation of expanding the fishing capacity in the absence of effective and restrictive management actions may exacerbate overexploitation risk. While considering social, legal and economic drivers fostering fleet growth, a bottom-up governance approach for the well-being of small-scale fishers is greatly necessary.

3.3.4 Impacts on water and energy security

Climate change affects water security adversely (Al-Jawaldeh 2022; Daoudy et al. 2022; Marangoz and Daloglu 2022). It can substantially decrease water yield, surface runoff, groundwater recharge, and baseflow in the Mediterranean region (Pulighe et al. 2021). Some studies emphasised on this effect for Mediterranean countries, like Egypt (Alkhawaga et al. 2022), Morocco (Hadri et al. 2022), Algeria (Bouregaa 2022), Türkiye (Gümrükçüoğlu 2022), Palestine (Sarsour and Nagabhatla, 2022), and Cyprus (Gökçekuş et al. 2022). Also, Iglesias (2011) highlighted challenges to water resources in Mediterranean countries and outlined the risks and opportunities for water under climate change. Chenoweth et al. (2011) predicted that precipitation would decline 10 percent in the region by both the middle and the end of the century. It will not significantly change per capita water resources in the North, while it will markedly reduce per capita water resources in the eastern Mediterranean.

Likewise, it is expected that climate change exacerbates the challenges regarding energy security in the Mediterranean region (Lange, 2019). Major climate impacts including increasing temperatures and decreasing precipitation will cause a growing number of heat waves and enhanced droughts, particularly in urban areas, and the subsequent scarcities of both water as well as energy (Lange 2019, 2022). To tackle climate change and its effects on energy security, Mediterranean economies need mitigation and adaptation strategies including enhanced efficiency of resource use, integrated technology assessments regarding electricity generation, and a stronger reliance on renewable/solar technologies (Lange 2019). They are required to adapt an accelerated energy transition policy, and diversify their energy mix (MedECC 2020). It should be mentioned that climate change affects the pace of energy transition (Flouros 2022). Baglivo et al. (2022) suggested zero-energy buildings for energy security and to combat climate change.

To cope with energy and water scarcities, MedECC (2020) proposed a regional energy market integration and cooperation as a mitigating strategy. Besides, Lange (2019) recommended an integrated water–energy nexus concept. Furthermore, some studies have focused on the Water–Energy–Food (WEF) nexus to address water, energy and food security under climate change, including Bazzana et al. (2023), Zebakh et al. (2022), and Riccaboni et al. (2022).

3.3.5 Impacts on coastal infrastructures

Coastal infrastructures in general, and ports in particular, are affected by different risks which can be increased by climate change in terms of stability and, fundamentally, in terms of functionality, mostly associated to increased coastal flooding and overtopping due to SLR (e.g., Sánchez-Arcilla et al. 2016; Arns et al. 2017; Izaguirre et al. 2021).

About 150 million people live in coastal areas and port cities in the Mediterranean (Galeotti 2020). It is expected that by 2050, for the lower sea-level rise scenarios and current adaptation measures, 10 of the 20 global cities with the highest increase in average annual damages are in the Mediterranean, located in Morocco, Algeria, Libya, Egypt, Palestine, and Syria (Galeotti 2020). Erosion and flooding are two major threats to Mediterranean coasts and will cause damage to human settlements (Rizzetto 2020).

Furthermore, potential consequences of climate change may impact Mediterranean airports, putting them at risk (De Vivo et al. 2022). Thus, airports located in coastal areas would be at risk of coastal flooding, which could be increased under SLR. Yesudian and Dwason (2021) conducted a global analysis of SLR risk for airports located in the Low Elevation Coastal Zone in terms of expected annual route disruption. In the Mediterranean, three airports were ranked in the top 20 by risk by 2100 which are Venice and Pisa in Italy, and Ioannis Kapodistrias Intl in Greece.

In coastal areas, SLR is the most important and likely climatic change-driver to affect infrastructures in general (Azevedo de Almeida and Mostafavi 2016), and transport networks in particular (Demirel et al. 2015). This is especially evident when coastal plains supporting such infrastructures are flooded episodically or permanently (e.g., Armaroli et al. 2019; Antonioli et al. 2020). In some cases, SLR will increase the number of disruptions currently taking place under the impact of storms in transport networks close to the shoreline such as the coastal railway along

Catalonia (Jiménez et al. 2018). The location of such infrastructures very close to the shoreline significantly increases the risk due to a high exposure that usually forces them to implement specific protection measures (e.g., see Pranzini (2018) for protection works in Italian coastal railways). In any case, it should be kept in mind that these infrastructures will be subject to greater risks of disruption not only due to increased overtopping under SLR, but also due to a future scenario of narrowing protective beaches in front of them due to SLR-induced erosion.

For the Thessaloniki area in Greece, Papagiannakis et al. (2021) estimated that under a SLR of 0.5 m and 1 m, about 1.87% and 3.07% respectively of the total length of the coastal road network will be covered by the sea by 2100, and the access road to the airport might be interrupted. For Türkiye, Karaca and Nicholls (2008) found that capital loss of the impacts of a 1–m rise in sea level could be significant (about 6% of current GNP). For Malta, Attard (2015) highlighted that environmental change could heavily damage the islands' infrastructure and disrupt the transport systems.

Izaguirre et al (2021) estimated an increase in risk for Mediterranean ports by 2100 under the RCP8.5 scenario, which changes from medium or low risk to very high or high future risk, respectively due to increased overtopping and coastal flooding risk. The western African Mediterranean ports were identified as subjected to very high risks. In addition to this, it has to be considered indirect impacts such as the highlighted by Christodoulou et al. (2019), who estimated that the indirect impacts on the operations of Mediterranean ports due to possible disruptions in Northern European ports can be considerable.

At regional scale, Sierra et al. (2016) assessed the impact of SLR on the operability of harbours along the Catalan coast in the western Mediterranean due to increasing overtopping during storms. They found a significant increasing risk in nearly all harbours under a high-end scenario of SLR of about 1.8 m, although results obtained for the median RCP8.5 scenario were significantly less risky.

In Egypt, the Nile Delta’s four principal fishing harbours are at high risk (Abutaleb et al. 2017). Port Said in the Nile Delta would be most affected in MENA (Dasgupta et al. 2009), and the economic damage due to the 0.5 m and 1.25 m SLR scenario is estimated to be more than $2.0 billion and $4.4 billion, respectively (El-Raey et al. 1999). This number for Rosetta is expected to be $2.9 billion (El-Raey, 2010). Refaat and Eldeberky (2016) estimated that almost 7% of the Nile delta area would be at risk of inundation due to future sea-level rise. Also, El-Masry et al. (2022) predicted that climate change might damage the coastal infrastructure in El Hammam-EL Alamein, and 34 to 36 (about 46.5% to 49.3%) of the existing coastal resorts could be inundated. For Morocco, Kasmi et al. (2020) highlighted the risk of erosion and soil loss in response to SLR (the loss of more than 50% of width with a 2m SRL scenario on many beaches). In the Tangier Bay, Morocco, Snoussi et al. (2009) noted that coastal defences and the port, tourist coastal infrastructures, the railway, and the industrial area are expected to be at risk due to climate change, and estimated that erosion of the shoreline would affect nearly 20% of the total beach areas by 2050 and 45% by 2100. Snoussi et al. (2010) calculated climate change impacts on the various Moroccan coasts, finding that 70% of most of the urbanised sections of the Tetouan coast would suffer from erosion,

In Israel, Zviely et al (2015) found that SLR is expected to cause extensive damage to port infrastructure, including seaports, power plants, marinas, desalination plants, sea walls, detached breakwaters, and bathing beach infrastructures, and to the vessels moored inside, as well. For 0.5 m and 1 m SLR, respectively, by costing approximately US$200 million and US$500 million (0.07% and 0.17% of Israel's GDP for 2012), the current level of operation of these infrastructures can be maintained (Zviely et al. 2015).

Finally, in terms of existing coastal protection measures, one of the most sensitive structures to SLR are parallel breakwaters since their capacity of protection depends on the relative height with respect to mean water level which controls wave energy transmission. Consequently, sea-level driven changes in wave characteristics and the structure relative height may significantly change their design conditions and increase the exposure of the protected area (Arns et al. 2017). In simple terms, the (economic) impact will be that associated with the need to increase the height of the structure to maintain its design conditions. As an example, Vousdoukas et al. (2018) estimate that upgrading existing coastal protection would imply increasing elevations by an average of at least 25 cm by 2050 and by more than 50 cm by 2100, although local required increments can be significantly higher. The importance and relevance of this impact along the Mediterranean will be controlled by the local conditions of the existing structures, although due to the extensive and intensive use of parallel coastal breakwaters as a protection measure it is expected that one of the areas with the greatest impact will be the Italian coast.

3.4 Impacts on the human systems

3.4.1 Impacts on the cultural heritage (natural and built)

Coastal regions remain crucial as areas of increased exposure to risk and increasing vulnerability towards climate change (*high confidence)* (IPCC 2022). The potential impact on natural and built heritage is caused both by on-going variations of climate and environmental parameters responsible for slow cumulative damage processes and by hydrometeorological extreme events.

In coastal areas, natural landscapes, archaeological sites and monuments are exposed to an aggressive and worsening environment, characterised by local land subsidence, coastal flooding and erosion (see *Chapter 2*) under the IPCC-RCP8.5 scenario estimated for 2100 a potential loss of Mediterranean coastline of about 148 km^2, impacting a coastline length of about 400 km (Antonioli et al. 2020).

Sea level rise risks submerging natural landscapes and built heritage. The Mediterranean coast includes several natural landscapes with their wildlife, such as the biodiverse wetlands of Doñana National Park, Spain (Camacho et al. 2022); Camargue on the delta of the Rhône River, France (Fraixedas et al. 2019). Detailed maps of the UNESCO cultural World Heritage Sites (WHS) located in the coastal zone at risk, and their projections to 2100 have been reported by Reimann et al. (2018), who, based on the analysis of spatially explicit WHS data and the development of an index-based approach, show that of 49 cultural WHS located in low-lying coastal areas of the Mediterranean, 37 are at risk of flooding for a 100-year return period and 42 from coastal erosion, already today. Until 2100, flood risk may increase by 50% and erosion risk by 13% across the region. Projections are provided under RCP2.6, RCP4.5 and RCP8.5. The most famous city at risk is Venice, sinking for the combined action of sea level rise and local land subsidence (Lionello et al. 2021; Camuffo 2022). In the long run, the built heritage risks to be transformed in underwater archaeological sites as it has happened for Capo Rizzuto (southern Italy), Pavlopetri and Peristera (Greece), Alexandria (Egypt); Caesarea Maritime (Israel); Kizlan (Türkiye), and several other Mediterranean harbours (Marriner et al. 2017). At present, storm surges are affecting buildings and archaeological sites. In the future, this challenge will continue with increasing frequency of occurrence and flooding depth.

The available projections of the impact that climate change will have on built heritage in terms of slow cumulative deterioration processes developed in the framework of the two EU funded programs Noah's Ark (Sabbioni et al. 2010; Bonazza et al. 2009a,b) and Climate for Culture (Leissner et al. 2015), highlight that the Mediterranean coastal heritage sites are likely expected in the far future (2071–2100):

- to undergo more than 30 events per year of relative humidity cycles equal to 75.5%, implying a potential risk of decohesion and fracturing of porous building materials, such as sandstones, mortars and brick, caused by crystallisation pressure of soluble salts (Camuffo 2019). Salt weathering is mainly driven by a phase change. The damage arises during the crystallisation-dissolution cycles, which occur under precise temperature and humidity conditions. Non-hydrated salts, such as sodium chloride (NaCl), crystallise at a fixed relative humidity (RH) virtually independent of temperature (RH threshold = 75.5%), whereas phase transitions in hydrated salts, such as sodium sulphate, are sensitive to both relative humidity and temperature (Bonazza 2022);

- to presumably experience higher level of biodeterioration, with value of total biomass accumulation from 5 to 15 mg cm^{-2} (Sabbioni et al. 2010);
- to undergo surface recession linked to chemical dissolution of 5–35 µm yr^{-1}, particularly monuments in marble and compact limestone located in highly polluted coastal areas (Bonazza et al. 2009a);
- to increasingly suffer from thermal stress caused by solar radiation with more than 150 events/year of internal tension > 20 MPa. This threshold of internal tension is considered particularly dangerous for marbles and can cause decohesion and powdering (Bonazza et al. 2009b).

Examples of the projected change in the yearly frequency of the NaCl crystallisation cycles calculated for building materials exposed to indoor climate variations are reported in **Figure 3.7**. This map has been expressed in terms of change as a difference between the far future (2071–2100) and the recent past reference period (1961–1990). The projection shows a slight decrease of the structural risk for the built heritage in the whole Mediterranean coastal area.

Only recently research started to focus on the development of projections of extreme events (i.e., heavy rain, flash floods, drought) linked to climate change addressed to assess the risk consequently imposed on natural and cultural heritage. This has been specifically faced in the framework of two EU funded Projects ProteCHt2save and STRENCH. The analysis done demonstrated that the impact linked to extreme variations of precipitation and temperature on monuments and archaeological sites in the Mediterranean regions is likely to increase in the near and far future (Bonazza et al. 2021).

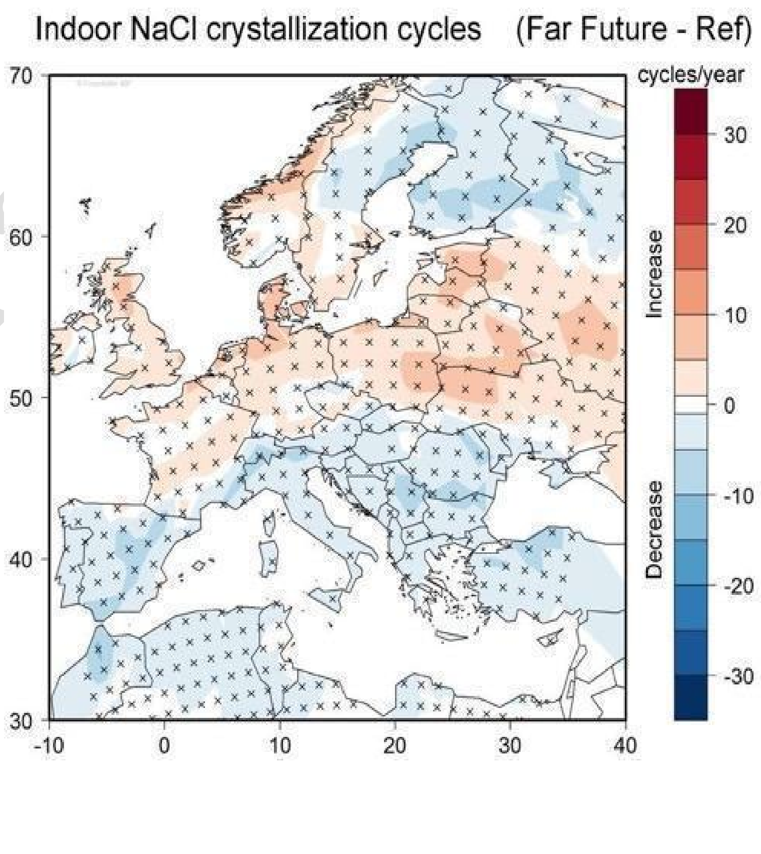

Figure 3.7 | Projected change of the yearly frequency of the NaCl crystallization cycles indoors, calculated as a difference between the far future (2071–2100) and the 1961–1990 reference period. Project Climate for Culture, simulation for an unconditioned building type 02 (average brick structure), under the RCP4.5 emission scenario (Leissner et al. 2015)

3.4.2 Impacts on the human health

Impacts of climate and geological hazards on human health

The Mediterranean Basin is one of the world's regions where climate and geological variables change the most. Serious health issues can emerge from the disrupted Mediterranean hydrological cycle causing extreme events such as floods and fires on coastal areas. In addition, coastal populations are the most vulnerable to sea level rise.

The increase in storm-induced floods and gradual inundation will be accentuated in the future through climate change and this can lead to water-borne and respiratory diseases. The increased atmospheric pressure during thunderstorms can lead to the occurrence of severe asthma epidemics and initiate Idiopathic Spontaneous Pneumothorax (ISP). Increased humidity can also lead to mould allergies and the development of asthma in susceptible individuals (Guéan et al. 2018).

Extreme events, such as floods often also disrupt medical care, with a particular impact on vulnerable populations such as those with chronic illnesses. Hospitals may be evacuated, transport of medication is challenged etc. In addition, electrical failures impact critical infrastructure (power, water, sanitation and sewer), with potential associated infectious diseases (waterborne pathogens). The impact on mental health is also to be considered, with potential post-traumatic disorders, depression.

The rising temperatures causing droughts, fires and heat waves are a serious threat to health in Mediterranean populations. Extreme droughts, by impacting freshwater resources, can have public health problems, including shortages of drinking water and poor-quality drinking water. Indeed, the reduced river stream can increase the concentration of pollutants in water and cause stagnation. Having water available for drinking, cleaning, sanitation, and hygiene is crucial to reduce many diseases. In the Mediterranean:

● 30% of the population live in water-scarce countries,

● 220 million people suffer from water scarcity,

● 26 million do not have access to safely-managed drinking water services,

● 160 million do not have access to safe sanitation (UNEP/MAP and Plan Bleu 2020).

Moreover, extreme heat results in excess death and illness through heat stroke, heat exhaustion, and exacerbation of chronic illness. In addition, heat exposure triggers multiple physiological mechanisms that cause damage to the brain, heart, intestines, kidneys, liver, lungs, and pancreas. Lastly, more frequent wildfires (naturally or human induced) will impact air quality, affecting particularly people with asthma, Chronic Obstructive Pulmonary Disease (COPD), or heart disease, and children, pregnant women, and firefighters are especially at risk.

Rising sea level consequences on wet and dry areas in coastal MED increases the risk of drowning, injury and population displacement. It is also associated with a greater risk of exposure to mould from increased humidity, hence responsible for respiratory diseases. Saline water migrating upstream in freshwater systems increases salinity in rivers but also in groundwater basins, hence directly or indirectly affecting human coastal population nutrition, through lower crop production or reduced availability of safe drinking water. Associated health impact includes higher risk of hypertension or diarrheal disease.

Impacts of biological hazards on human health

Variable weather conditions (mainly temperature, rainfall and humidity) strongly influence the emergence of vector-borne diseases (diseases transmitted through insects) and water-borne diseases. Recently, several outbreaks have been observed and associated with local climatic changes in the Mediterranean basin region (Paz and Albersheim 2008; Paz et al. 2013). Currently, the main vector-borne diseases transmitted by mosquitoes and potentially exacerbated by the changing climate in the Mediterranean basin, are West Nile Fever, Dengue, Chikungunya, Malaria and Leishmaniasis (Paz et al. 2008). In addition, higher sea surface temperatures and heavy rainfall leading to an abrupt decrease in salinity can have a major effect on the abundance of pathogenic bacteria (Vibrio species) found in Mediterranean marine, lagoon and estuarine environments. These bacteria are recognized throughout the world as agents of gastroenteritis in humans resulting from the consumption of raw or undercooked seafood and serious infections caused by exposure to skin wounds to seawater (Guéan et al. 2018). In addition, when sewers carrying urban and industrial wastewater are overloaded, untreated sewage can flow into rivers, lakes and coastal areas. This can lead to greater exposure of populations to contaminants, inadequate sanitation and unsafe drinking water (UNEP/MAP and Plan Bleu 2020).

Impacts of chemical hazards on human health

Coastal populations suffer from the cumulative burden of environmental pollution resulting from the intense local activities and from upstream and inland development. When concentrated in small, confined, and overcrowded areas such as Mediterranean coastal zones, air and water pollution poses great threats to human health.

Two-thirds of the Mediterranean countries exceed the global WHO recommended threshold for air pollution from particulate matter and ozone even if air pollution has been linked to a broad spectrum of NCDs (diabetes, cardiopulmonary diseases, neurodegenerative diseases, etc.). In addition, high levels of noise caused by traffic can cause heart conditions and reduce cognitive functions in children.

With up to 100 µg m^{-3} 20 in some Mediterranean areas (world average: 39.6 µg of PM2.5 m^3, EU average: 14.2 µg of PM2.5 m^3) (UNEP/MAP and Plan Bleu 2020). In the Mediterranean, air pollution is the main environmental burden with 228,000 deaths (UNEP/MAP and Plan Bleu 2020). The impact of air pollution on health is generally much higher in SEMCs (South-East Mediterranean Countries) than in NMCs (Northern Mediterranean Countries). Egypt is the country in the world with the highest death rate attributed to ambient air pollution (UNEP/MAP and Plan Bleu 2020).

Agriculture, coastal tourism and recreation, transport, port and harbour activities, urban and industrial development, mining, fisheries, and aquaculture are all sources of marine pollution. Marine pollution refers to thousands of physical, chemical, and biological entities such as toxic metals, petroleum, plastics, manufactured chemicals such as pharmaceuticals or pesticides, excessive nutrient load from agricultural runoff or sewage, Harmful Algal Blooms (HABs) etc. The Mediterranean is one of the world's regions most affected by pollution with half of its coastal waters not achieving good environmental status (UNEP/MAP and Plan Bleu 2020). Above a certain level, such agents threaten the health of living beings. Coastal populations are particularly exposed to sea pollution (especially populations from low and middle-income countries) (Landrigan et al. 2020). In the Mediterranean, more than 500,000 deaths occur each year as a result of unhealthy environments. The rate of these premature deaths is 2 to 3 times higher in the South-East Mediterranean countries and the Balkans than in EU countries (UNEP/MAP and Plan Bleu 2020). People can be exposed to chemicals through dermal contact, ingestion, inhalation or during development. Methylmercury and PCBs are ocean pollutants whose human health effects are best understood. Exposures of infants in utero to these pollutants through maternal consumption of contaminated seafood can damage developing brains, reduce IQ and increase children's risks for autism, ADHD and learning disorders. Adult exposures to methylmercury increase the risks of cardiovascular disease and dementia. Because of their small size, microplastics are easily absorbed by organisms. Recently, studies showed that microplastics are present in the human bloodstream and that microplastics cause damage to human cells at the levels known to be eaten by people via their food (Danopoulos et al. 2022; Leslie et al. 2022). In addition, plastics can provide transport and shelter to hazardous microorganisms, including vectors for human disease. Toxic chemical pollutants in the sea have been shown capable of causing a wide range of diseases in humans. Manufactured chemicals such as phthalates, bisphenol A, flame retardants or perfluorinated chemicals can disrupt endocrine signaling, reduce male fertility, damage the nervous system, increase the risk of cancer and cause cardiovascular and metabolic diseases. Harmful algal blooms (HAB) produce potent toxins that accumulate in fish and shellfish. When ingested, these toxins can cause severe neurological impairment and rapid death. HAB toxins can also become airborne and cause respiratory disease. Pathogenic marine bacteria cause gastrointestinal diseases and deep wound infections (Landrigan et al. 2020).

There are many thousands of types of man-made marine pollution for most of which the available knowledge is very scarce, especially on the levels of exposure and magnitude of human health impacts. The majority of manufactured chemicals have never been tested for safety or toxicity: Only about 700 out of 70,000 chemical substances on the market have been studied for their risk impacts (UNEP/MAP and Plan Bleu 2020). In addition, pollutants are rarely present in the environment in isolation but instead are found in complex mixtures. This creates even more uncertainties about the possible combined effects of exposure to mixtures of contaminants. Lastly, there are synergistic effects between climate change and chemical pollution. For example, climate change appears to increase the toxicity of metals and increase the frequency of toxic algal bloom and pathogenic bacteria outbreaks as a result of rising temperatures and extreme precipitation events (Cabral et al. 2019).

Despite the severity of sea pollution and growing recognition of its effects on health, significant uncertainties remain. Because of these knowledge gaps, the impacts of sea pollution on human health and well-being are surely underestimated. So, in order to protect the public from exposure to such harm, decision-makers should adopt a precautionary approach and control pollution in a coordinated manner because pollution is transboundary and all of the health impacts of sea pollution fall disproportionately on vulnerable populations of South and Eastern Mediterranean Countries.

Final remarks

These described risks are projected to increase under future climate and economic development scenarios. The developing countries, mainly in North Africa and the Levant, are at highest risk. There is therefore a need for better health management and policies including tailored early warning systems to rapidly detect potential public health threats and trigger alerts. In addition, epidemiological investigations should be conducted to better monitor the health of Mediterranean coastal populations and guide sound public health and environmental policies.

3.5 Impacts on the natural systems

3.5.1 Impacts on coastal low-lying, wetlands and deltaic systems

The Mediterranean wetlands occupy 2 to 3% of the land area of the Mediterranean basin and include a diversity of ecosystems, including lagoons and salt marshes, freshwater lakes, karstic cave systems, temporary ponds, artificial wetlands such as reservoirs, Salinas, fishponds and rice paddies, small and scattered peatlands, and one of the longest rivers in the world. At the same time, 30% of the region's vertebrate species depend on Mediterranean wetlands (Taylor et al. 2021), and across history wetlands these ecosystems have contributed multiple ecosystems services to different civilizations and cultures, and the identity and well-being of communities, making them an important component of Mediterranean social-ecological systems (Balbo et al. 2017).

Since 1900, 50% of the wetlands have been lost, with significantly high figures observed for various wetland ecosystems across the region, and 73% of marshes have been drained in northern Greece since 1930, 86% of the 78 most important wetlands of France were degraded in 1994, 60% of primary wetland area has been lost in Spain; and 84% of the wetland area in Medjerda Basin, Tunisia, was lost during the 20th century (Balbo et al. 2017). While this trend may have slowed down in recent years (Balbo et al. 2017), the level of protection varies and recent research indicates that wetland sites in the southeast of the Mediterranean basin combined low or no protection cover with the highest increases in temperature and losses in natural habitats (Leberger et al. 2020). In the Mediterranean, the largest coastal wetlands are found in delta areas, such as those of the Rhône (France), Nile (Egypt), Po (Italy) and Ebro (Spain) rivers. The deltaic areas are vulnerable to human modification and climate change, with sea-level rise being considered a key threat leading to increased flooding, coastal erosion, extreme events, salinity intrusion and habitat degradation.

Cultural uses of coastal wetlands, and particularly the expansion of irrigated agricultural areas and urban development, have led to significant and complex changes to Mediterranean coastal wetlands, with impacts on hydrological fluxes and the salinity of surface water, and in turn affecting ecological communities. For example, in the case of Doñana wetlands, situated within the delta of the Guadalquivir River (south-west Spain), 80% of its original marsh surface area has been converted, mainly for agriculture. Agricultural runoff, intense urbanization, inadequate wastewater treatment, and extensive hydrological modifications have led to high nutrient loading to the remaining wetlands (Green et al. 2017). Furthermore, water management associated with the expansion of coastal tourism, combined with the effect of climate change, could lead to reductions in groundwater storage and salt water intrusion (Maneas et al. 2019).

Rising temperatures will likely increase evapotranspiration rates, which combined with reduced rainfall will enhance the plant water stress and will require higher amounts of water for crop irrigation. These conditions will influence the water biota by favouring species that are more tolerant to drought (high agreement, medium evidence). Macroinvertebrate communities are moderately resilient to salinity increases but salinity increases to polyhaline conditions cause drastic community simplifications in terms of functional evenness, and loss of biodiversity (Muresan et al. 2020). On the other hand, temperature and salinity increases, combined with insecticide exposure, contributed to a decline in zooplankton diversity but increased temperature was associated with increased abundance while increased salinity was associated with reduced abundance across all zooplankton groups (Vilas-Boas et al. 2021). Excessive nutrient loading also leads to changes in the biotic community and may lead to dominance by blue-green algae (cyanobacteria) or floating plants, triggering losses in biodiversity and ecosystem services. Eutrophication and higher temperatures work in combination to reduce levels of dissolved oxygen, causing lethal and non-lethal effects (Green et al. 2017).

Decreases in the mean precipitation and precipitation variability during the dry season are likely to have profound effects on Mediterranean wetlands (high agreement, medium evidence). However, the impact of climate change on wetlands will be tightly related to changes in water deficits, which are currently heterogeneous across the Mediterranean region (**Figure 3.8**). In a study investigating how climate change will affect the values and functions of Mediterranean seasonally-flooded wetlands with emergent vegetation, using future projections of the relevant climatic variables under two Representative Concentration Pathway scenarios assuming a stabilization (RCP4.5) or increase (RCP8.5) of greenhouse gases emissions, increases of water deficits at most localities around 2050 under both RCP scenarios were recorded. Simulations performed under current conditions show that 97% of localities could have wetland habitats in a good state. By 2050, however, this proportion would decrease to 81% and 68% under the RCP4.5 and RCP8.5 scenarios, decreasing further to 52% and 27% by 2100. Results from this study indicate that wetlands can persist with up to a 400 mm decrease in annual precipitation, with this resilience being attributed to the semi-permanent character of wetlands and their capacity to act as reservoir. Countries at the highest risk of wetland degradation and loss were identified as Algeria, Morocco, Portugal and Spain (Lefebvre et al. 2019).

A rise in sea level of 0.16 m (RCP8.5) in the short term (2026–2045) and 0.79 m (RCP8.5) by the end of the 21st century (2081–2100) are predicted by the CMIP5 models. On the other hand, the extreme proposed scenarios indicate rises from 1.35 m to 1.92 m by the end of the 21^{st} century. The IPCC scenarios will lead to the loss of coastal wetlands (high agreement, robust evidence). For example, the IPCC scenarios are expected to lead to the loss of 96 km^2 of the Júcar River Basin District, Spain, wetlands having high ecological value and protected under the RAMSAR convention and as part of the Natura 2000 Network. The high-end scenarios significantly increased the areas at high risk to 142 km^2, and impacted an urban area of 27 km^2 (Estrela-Segrelles et al. 2021). Sea level rise interacts with other climatic, for example temperature rise and frequency of storms, and non-climatic drivers such as the lack of sedimentary contributions due to the regulation of riverbeds, the overexploitation of water resources and coastal aquifers, and associated coastal erosion and seawater intrusion (*high agreement; limited evidence*) (Maneas et al. 2019; Estrela-Segrelles et al. 2021; Ferrarini et al. 2021; Rodríguez-Santalla and Navarro 2021).

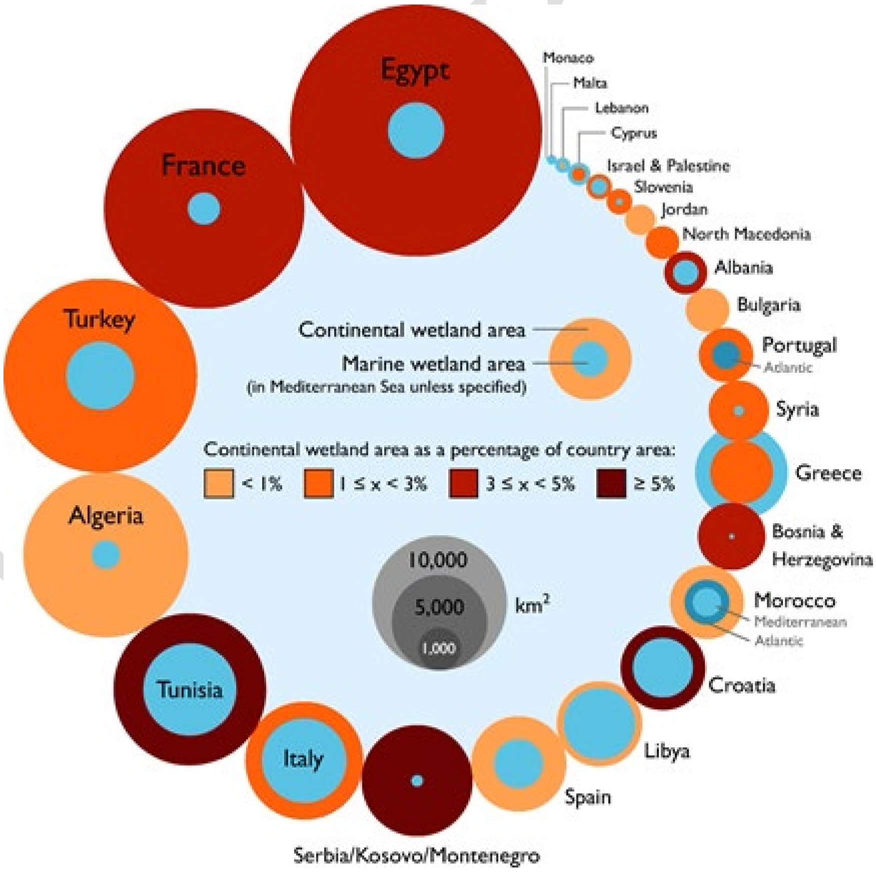

Figure 3.8 | Overview of the extent of Mediterranean wetlands. The area of each circle is proportional to the wetland area. Yellow-orange-red circles represent continental surface wetlands; shading indicates the percentage of each country covered by wetlands. Blue circles represent marine wetlands (< 6 m water depth at low tide) on the Mediterranean coast of each country, plus Atlantic coasts for Morocco and Portugal. Data from Perennou et al. (2012) and MWO (2018), as presented in Taylor et al. (2021).

[Placeholder] Figure 3.9 | Contemporary (1981–2013) annual water balance (precipitation minus evapotranspiration) for each of the 229 Mediterranean localities under constant flood conditions. The thirteen localities for which seasonal flooding patterns could not be simulated under the current climate conditions are shown in grey.

3.5.2 Impacts on coastal ecosystems

Coastal ecosystems and people are significantly facing risks from sea-level rise which are suscibitable to increase tenfold before 2100 if no adaptation options and mitigation scenarios have been taken into consideration and implemented in accordance with Parties to the Paris Agreement. With extreme emission scenarios that do not limit warming to 1.5°C, the rising sea level will increase the risk of coastal erosion and coastal land submergence, loss of coastal habitat, and ecosystem loss. It will also cause groundwater salinization, compromising coastal ecosystems and livelihoods. The Mediterranean is known for its micro-tidal nature, which would increase the susceptibility to coastal hazards related to climate change. The coastal zone refers to the physical region from the edge of the continental shelf to the intertidal and near-shore terrestrial area. It includes a wide range of near-shore terrestrial, intertidal, benthic, and pelagic ecosystems with some main categories are estuaries, coastal marshes, mangroves, seagrass, and benthic systems (Yang 2008). Coastal ecosystems are highly impacted by a combination of conditions; including sea level rise, coastal erosion, acidification, and other climate-related ocean changes. It is also experiencing some adverse effects derived from urbanization and human activities on the ocean and land. The Mediterranean Basin is experiencing continuous changes in environmental conditions, creating major challenges and introducing new vulnerabilities to its natural and human systems. Coastal ecosystems could progressively lose their ability to adapt to climate-induced changes and consequently their services, including acting as coastal protective barriers (Oppenheimer et al. 2019). Loss of breeding substrate, including mostly coastal habitats such as sandy beaches, can reduce the available nesting or pupping habitat for land-breeding marine animals and, seabirds.

Coastal erosion is a major cause for the loss of ecosystem services provided by beaches, as most habitats in the coastal zone could be affected, degraded, or disappear as erosion progresses (Paprotny et al. 2021). In a study to evaluate the effect of coastal erosion along the northern Mediterranean basin (the European coast) for ecosystem services for RCP4.5 and RCP8.5 scenarios and estimate a 5% decline in services by 2100 under RCP8.5 showing high spatial variability with the largest estimated declines in the Eastern Mediterranean section. The value of ecosystem services declined by 323 million euros between 2000 and 2018. The majority of the coastal services decline was mainly attributed to forest contraction and intense agriculture, which was partially compensated for by the expansion of wetlands, mainly salt marshes. Salt marshes are among the most climate-affected coastal habitat, although it is well-known for wave attenuation and for their role in reducing erosion and flooding (Kirwan et al. 2010; Temmerman et al. 2012; Arkema et al. 2013; Vuik et al. 2016; Temmerman et al. 2023). The erosion-destroyed salt marshes or sand dunes along the coastlines are more endangered than others. Saline bodies, estuaries, inland marshes, and natural grasslands would also be among the most affected habitats terms.

Coastal erosion has been affecting most of the Mediterranean coastal zones with growing intensity along the European coasts due to climate change (Terefenko et al. 2018a, 2018b, 2019; Paprotny et al. 2021). The Mediterranean hotspots of erosion impacts are discussed in detail in Section 3.2.2 of this report. The major losses were in beaches, sands, and dunes and the most affected countries in the Mediterranean basin would be Albania, Greece and France and would be among those losing the largest share of their coastal ecosystem services. Erosion could also create a new challenge of inundation, affecting the coastal lagoons by losing their beaches and changing their characteristics as well as services. Climate-induced saltwater intrusions could also affect vigorously many other coastal habitats (Barlow and Reichard 2010).

The annual damage is projected to rise by 90 to 900 times if future scenarios of climate change and socio-economic trends are combined. Rising sea levels increase storm wave frequency, and reduce the sediment supply to the coast, while anthropogenic degradation, and coastal transformation would lead to an irretrievable loss of ecosystem services (Barbier et al. 2011; Ranasinghe 2016).

With regards to systems and habitats close-to-shore, it is still uncertain how the anthropogenic inputs of CO_2 and the resultant rapid acidification would affect the coastal systems; this is mainly due to the lack of data. However, there is some research work that has been done in the Mediterranean (Rodrigues et al. 2013; Peled et al. 2018) concerning the changes in ocean chemistry and studies how this reflects on marine and coastal ecosystems first, then on the socio-economic sectors. These studies suggested that tourism and recreation, red coral extraction, and fisheries are the most important affected sectors (Rodrigues et al. 2013). Meanwhile, the study undertaken by Ramajo et al. (2019) and others have suggested treating the acidification problem with seagrasses that may provide "refugia" from ocean acidification for associated calcifying organisms, as their photosynthetic activity may raise pH above the thresholds for impacts on calcification and/or limit the time spent below some critical pH threshold. It is proved that grass covers are effective in decreasing runoff and reducing soil losses particularly in summer and during intense events (Ramajo et al. 2019). Any changes in sediment supply, industrial development, and urban processes would enhance the vulnerability of the coastal sandy beaches, saltmarshes, and mangrove forests to sea-level rise. In addition, mangroves are experiencing compound threats due to ocean warming, sea level rise, nutrient pollution, and the low-oxygen zones formed as a climate change consequence and this risk is escalating to be very high by the end of this century (Cooley et al. 2022). Normally, blue Carbon ecosystems (mangroves, saltmarshes, and seagrass meadows; see glossary) are known for their high accumulation rate of carbon (Macreadie et al. 2019) with uncertainties of carbon accumulated and CO_2 release (Macreadie et al. 2019; Saderne et al. 2019).

The Mediterranean aquifer systems and other water bodies are experiencing high exploitation levels with increased water demand and salinization. In addition, the growing population increases the human demand for water and this put additional pressure on water resources and increases the severity of water scarcity in a dramatic pattern (Iglesias et al. 2018; Bond et al. 2019). The long-term changes induced by climate, particularly marine heatwaves, are extremely affecting marine ecosystems; causing mortality or bleaching of coral and mass mortalities of other species leading to a decline of kelp forests, loss of seagrass-meadow habitats, invasion of new species, and acute changes in community structure of several marine ecosystems. Harmful blooms of algal species and other waterborne disease increased as a consequence of climate change and this disturbance threatens human health and livelihoods of coastal communities (see *Chapter 2*). However, most of these risks are still uncertain (Reimann et al. 2018) at transboundary and regional levels to address the major challenges among Mediterranean countries.

3.6 Final remarks

Whatever the causes triggering the formation of coastal water pollution, this creates an increasing concern in coastal areas due to its socio-economic consequences. Uncertainty remains as to indicate the drivers with the largest impact. This highlights the need for strong and influential cooperation at transboundary and regional levels to address the major challenges among Mediterranean countries.

With regards to systems and habitats close-to-shore, it is still uncertain how the anthropogenic inputs of CO_2 and the resultant rapid acidification would affect the coastal systems; this is mainly due to the lack of data.

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4 Managing climatic and environmental risks

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4.0 Executive summary and/or key messages

- **Adapting to coastal flooding**. Except for some experiments on relocation and nature-based solutions, current coastal management typically implements high-cost engineering protection, with potential adverse impacts on coastal landscape and biodiversity and associated ecosystems (*high confidence*). Solutions implemented so far, such as the MOSE barrier in Venice, are addressing near-term risk and will reach soft limits during the 21st century due to ongoing sea-level rise (*medium confidence*). The lack of consideration of climate change and sea-level rise in coastal flood risk management creates risks of lock-ins and maladaptation in the future (*high confidence*) (Section 4.2.1).
- **Adaptation to coastal erosion:** the efficiency of engineering protection to prevent erosion in the Mediterranean is decreasing due to sediment scarcity in coastal areas (*medium confidence*). Nature-based solutions, such as protecting *Posidonia* meadows and leaving banks of dead leaves on beaches, are receiving more attention and are increasingly implemented, but not to the scale needed to prevent current risks due to trade-offs with other aspects of coastal management such as cleaning beaches for tourism (*high confidence*). The implementation of nature-based solutions and relocation are limited by the lack of space and finance in many locations. Current management of coastal erosion generally overlooks the commitment to sea-level rise (*high confidence*). A more transparent communication and governance that considers potential lock-ins and opportunities resulting from the ongoing transformation of Mediterranean coasts could enable adaptation to future escalating erosion risks, avoiding short term interventions that may lead to maladaptation in the future (*medium confidence*) (Section 4.2.1).
- Managing coastal ecosystems' biodiversity loss: Mediterranean coastal ecosystems belong to those most at threat due to the rapid rate of regional climate change and human pressures (*high confidence*). Many Mediterranean coastal species and ecosystems are characterised by high rates of endemism and are already reaching their adaptation limits due to ocean warming and repeated marine heatwaves causing mass mortality and tropicalization. Rising temperatures, eutrophication, deoxygenation, acidification, sea-level rise and ongoing human activities such as habitats destructions, eutrophication and overfishing will cause further decline of ecosystems in the coming decades (*high confidence*). Yet, biodiversity losses can be limited by adequate conservation measures while keeping climate change below 1.5°C with no or small overshoot by adaptation (*medium confidence*) (Sections 4.2.3, 4.2.4 and 4.3).
- **Adapting to pollution:** In the Mediterranean region, there is a clear mismatch between the geographical and temporal scales of pollution management actions. Even though management is proposed at different levels, i.e. at the source point of pollution and at the

receiving system, both targets require continued long-term monitoring and adaptive recovery management plans, which emphasise institutional experimentation and learning by doing (*high confidence*). Monitoring and assessment of the adaptation actions are essential for the design and implementation of follow-up intervention strategies (*high confidence*). To this end, it is necessary to quantify ecosystem quality using different indicators. In general, adaptation at the source point is more efficient as it is usually simpler to implement, long-lasting, easier to monitor, and cheaper (*medium confidence*).

- **Managing non-indigenous species:** Policies to address non-indigenous are best implemented at the regional level. While non-indigenous species have been a reason for biodiversity loss even before climate change effects were significant, the loss of apex predators (especially in the marine environment) is a major catalyst for the colonisation and expansion of non-indigenous species (*high confidence*). Further biodiversity losses can be limited by keeping climate change below 1.5°C with no or small overshoot and by adaptation. Non-indigenous species entries through the Suez Canal and limits to fishing through large and sustained no-take protected areas are some means among others (*medium confidence*) (Section 4.4).
- **Native species and biodiversity:** Many native expanding (exploding) populations have increased a foothold due to changing ambient conditions (*medium confidence*); these get much less attention among researchers and scientific literature but are exacerbated by climate change (Section 4.4).
- **Managing freshwater scarcity:** Observed adaptation to reduced water quality and availability often focuses on increasing water supply e.g. through storage (*high confidence*). To limit future risks of water scarcity, adaptation measures aiming at reducing the demand are increasingly needed in addition to protecting or increasing water resources (*high confidence*). Adaptation limits will be reached above 3°C of global warming in the North-East Mediterranean and possibly earlier in the East and South Mediterranean, with the risks of compromising autonomous adaptation of coastal terrestrial, freshwater, and brackish water ecosystems if their needs for water are not sufficiently considered (*high confidence*) (Section 4.2.4).
- **Enhancing science-policy interaction:** Engaging science in dialogue with policymakers, stakeholders, and citizens, strongly contributes to raising awareness and knowledge, as well as to building trust. The most promising opportunity for establishing science-policy dialogue is during the planning process. Turning stakeholders into partners through participation, engagement, and ownership of the plan is the best guarantee for the plan's implementation (*high confidence*). In addition, the process of preparation of plans is a unique opportunity for establishment of permanent structures for science-policy interaction. Connecting these two worlds cannot happen spontaneously, without a dedicated and organized framework designed to meet the differences and to overcome barriers (Section 4.7).
- **Augmenting regional cooperation:** The complexity of the world of today makes the potential collaboration very challenging; among key barriers are lack of understanding and trust. Regional examples (MAP, UfM, MedECC), national experiences, sub-national advisory boards, and governance network analysis results provide some recommendations. For detailed coastal adaptation planning more data is needed; however, uncertainty will remain so the phased approach, such as an adaptation pathway is recommended (Section 4.7.4).

4.1 Introduction

The Mediterranean coastal areas are exposed to a wide range of climate and environmental risks that can lead to significant pressures on the human communities and ecosystems in the region. Such present and potential future risks add to already existing multi-stressors and can have dire economic and societal consequences. Managing these risks effectively requires considering the economic, socio-cultural, institutional and technological contexts. To address and respond to these challenges, solutions and approaches that are based on a deeper understanding of these climate and environmental risks and the socioeconomic settings, as well as concerted efforts at national and regional levels are necessary.

This chapter intends to identify and examine different responses and management approaches that are employed in the Mediterranean coastal areas for coping with climate change and environmental risks to assess the existing policy-research interface. In this context, it assesses the effectiveness of existing and prospective responses, using a wide range of criteria, and presents best practices across the Mediterranean region. The chapter, therefore, begins by discussing adaptation to climate risks (including climate change), then solutions to pollution and non-indigenousinvasive species issues. This is followed by considering possible measures to reduce potential tsunami risk, then risk synergies (compound risks) and management considerations are examined as well as residual risks and barriers to effective responses. Thereafter, the important research policy interface and means to improve the uptake of research results by policy makers are considered. The chapter is then concluded with a number of examples of institutions in the Mediterranean (MedECC, UNEP/MAP Regional Activity Centers (RAC), Sea'ties initiative from the Ocean and Climate Platform and examples of research policy interface at the regional/local level policy making in France, Croatia (Coastal plans Šibenik) and Spain (Barcelona, Catalonia).

4.2. Climate change risks and adaptation

Mediterranean coastal regions are highly exposed to climatic hazards as, due to the micro-tidal environment and the generally stable coastline, communities have developed lifestyles adapted to non-dynamic water levels (MedECC 2020). As a result, a large number of social and economic activities take place at the coast and infrastructure is located in very close proximity to the sea. Rapid socio-economic development along the coast (Reimann et al. 2018) in combination with climate change, primarily sea-level rise (IPCC 2022), are expected to further exacerbate this high exposure to climate extremes such as storm surges, waves, and heatwaves. Direct impacts will include increased coastal flooding (frequency and intensity), coastal erosion, loss of wetlands (Schuerch et al. 2022), salinization of groundwater and agricultural land, warming and acidification of coastal waters, which may lead to damages to infrastructure (including critical infrastructure) and loss of life, affect food security and biodiversity. The next sections briefly assess the current status of coastal adaptation in the Mediterranean region, with a focus on flooding, erosion, coastal ecosystems, and water.

Categories of adaptation measures for each hazard		Current implemen-tation	Effective-ness up to 2050	Feasibility			Relation with other systems at risk			Type of adaptation limits up to 2050[1]	Confidence in the assessment	
				Technologi-cal	Economical	Socio-institutional	Economical develop-ment	Human wellbeing	Ecosystems		Evidence	Agreement
Coastal flooding	Protection	•••	••	•••	North: ••• South: ••	•••	+/-	+/-	Eng.: - NbS: +	Soft	••	•••
	Accommodation	•	•	••	•••	••	+	/	/	Hard	•	•••
	Avoidance[2]	•	••	•••	/	•	+/-	+/-	+	None	•	•••
Coastal erosion	Protection	•••	••	•••	•••	•/••	+/-	/	Eng.: - NbS: +	Hard[4]	•••	•••
	Accommodation	•/••	/	•••	/	•/••	+/-	/	NbS: +	Hard[4]	•	••
	Managed realinement[3]	•/••	•••	•••	North: •• South: /	•/••	/	/	NbS: +	Soft	••	•••
Coastal ecosystems	Autonomous adaptation (AA)	NA	•	NA	NA	NA	NA	NA	NA	Hard	•••	•••
	Measures sup-porting AA	•	••/•••[5]	•••	/	/	+/-	+	NA	Hard	•••	•••
	Technologies and Innovation	•	••	••	/	••	/	/	NA	/	•/••	••
	Socio-institutional adaptation	•/••	•[6]	••/•••	/	•/••	/	+	NA	None	•••	•••
Scarcity of coastal freshwater ressources	Increasing water supply	•••	•	•••	•/••	••	+/-	+/-	-	Hard	•••	•••
	Demand oriented adaptation	•/••	••/•••	•••	•••	•/••	+	+	+	Soft	•••	•••
	Improving water quality	•	••	•••	••[7]	•	/	+	+	Soft	••	•••
	Governance	•/••	•••[6]	/	/	•/••	+	+	+	Soft	••	••

Legend:

•••	high	+	positive	Eng.:	Engineering protection[8]
••	medium	-	negative	NbS:	Nature based solutions[8]
•	low	+/-	mixed	Soft:	Softs limits to adaptation[8]
		NA	not appropriate	Hard:	Hard limits to adaptation[8]

1: soft and hard limits to adaptation are defined as in the 6th Assessment Report of the IPCC.
2: avoidance consists in establishing setback zones. It currently dominates adaptation responses to coastal flooding within the relocation/advance/avoidance portfolio of measures in the Mediterranean region.
3: Though less implemented than engineering protection, managed realinement dominates adaptation responses to coastal erosion within the relocation/advance/avoidance portfolio of measures in the Mediterranean region.
4: due to lack of space and sediments to protect from erosion.
5: depending on ambition: efficient measures include large marine protected areas without fishing, system change in the agriculture sector resulting in a deep and rapid de-crease of intrants such as nitrates and pesticides).
6: this solution does not provide benefits if implemented alone, but it can enhance the effectiveness of other measures or become an enabler of transformational adaptation.
7: depends on policies and economical incentives supporting practices favoring water quality.
8: see definitions in the 6th Assessment Report of the IPCC.

Figure 4.1 | Effectiveness, feasibility, co-benefits, and trade-offs of coastal adaptation measures in the Mediterranean. The table summarises the assessment of *Section 4.2* and builds upon the IPCC AR6 WGII report (IPCC 2022).

4.2.1 Coastal flooding

Protection

In the context of coastal flooding, protection refers to the implementation of coastal structures or the restoration of coastal systems in order to reduce flooding risks in human areas. Analyses at regional and national scale have shown that protection can be cost-efficient around most urbanised low-lying areas in the Mediterranean (Hinkel et al. 2010; Lincke and Hinkel 2018) (*medium confidence*). Costs of protection represent up to 0.1 to 0.2% of the GDP in countries located in the South and Eastern Mediterranean region, including Tunisia, Morocco, Greece, Montenegro, Libya and Cyprus (Lincke and Hinkel 2018).

Prevention of coastal flooding in the Mediterranean cities, ports and coastal airports is typically taking place through coastal engineering protection (*high confidence*), including coastal infrastructures such as breakwaters, seawalls, barriers or mobile dams, mechanical wetlands and water management works (Zviely et al. 2015; Ciampa et al. 2021; Ali et al. 2022; De Vivo et al.

2022; Sharaan et al. 2022). Yet, engineering protection can have adverse impacts for coastal hydrodynamics and ecosystems (*high confidence*) (Masria et al. 2015; Schoonees et al. 2019, see *Section 1.2*). Coastal engineering protection can also be combined with nature-based solutions such as coastal wetlands and dune restoration or vegetization of the coastline, and with development priorities where road infrastructures offer the support for coastal protection, as shown for example in the Nile Delta (Sharaan et al. 2022).

There is evidence that coastal protection is not limited to managing current coastal flooding risks, but also considers current and future sea-level rise. For example, the MOSE barrier in Venice (Italy) has been implemented in response to more frequent chronic flooding. Yet, soft limits to adaptation could be reached within decades as the gates will be closed more frequently with continued sea-level rise, reducing ship traffic and lagoon water exchanges (Bednar-Friedl et al. 2022). Overall, there is *high confidence* that besides front-running cities and ports, the majority of cities and ports in the Mediterranean region have not started planning for coastal protection or any other adaptation strategy to future sea-level changes (Olazabal et al 2019; Mc Evoy et al. 2021; Reckien et al. 2023). For example, there is a limited number of ports with known coastal adaptation strategies in Spain and many coastal cities adaptation plans do not refer explicitly to future sea-level rise (Portillo Juan et al. 2022; Ruiz-Campillo et al. 2022). One particular challenge that has not received much attention so far is the projected change of flooding modes: many areas prone to overtopping or even unaffected by flooding during storms today are at threat of overflow in the future, which puts not only infrastructure but also human lives at risk. This is a gap of knowledge.

Accommodation

Accommodation consists in reducing the vulnerability of assets. It can be implemented at the level of building and infrastructure, for example by elevating electrical devices or avoiding basements in flood-prone areas, at the level of coastal flood management units for example., in combination with nature-based solutions such as wetland and dune restoration, or at the levels of institutions or governance by setting up alert systems and emergency plans or insurance products (Oppenheimer et al. 2019). While there is low evidence for coastal accommodation in the Mediterranean region, there is high agreement that accommodation is considered in behavioural patterns and in policies and can be supported by climate services such as coastal flood modelling (Zviely et al. 2015; Durand et al. 2018; Samaras and Karambas, 2021).

Relocation, avoidance and advance

There is evidence, meanwhile, of efforts to avoid further increase of urbanization in low-lying areas in the Mediterranean region, including in France and Portugal. This avoids an increase in exposure, which in the long term may require relocation. Such avoidance is prescribed in the form of setback zones in the Protocol on Integrated Coastal Zone Management in the Mediterranean (ICZM Protocol to the Barcelona convention 2008) and is included in the legislation in several countries. Although few studies exist, setback zones steering development away from the floodplain appear to have the potential to significantly reduce the impacts of future coastal flooding (Lincke et al. 2020). Besides these efforts, there is high agreement but limited evidence that maladaptive land use planning is taking place, as shown by local coastal development strategies being often inconsistent with national adaptation targets, as exemplified in French Mediterranean coastal municipalities (Robert and Schleyer-Lindenmann 2021). For existing coastal settlements and assets retreat is less considered in response to flooding than for erosion. Advance toward the sea in the Mediterranean region is taking place in Monaco, where space is limited, and large financial resources are available. The infrastructure, which forms a peninsula extending the harbour, has been designed for a lifetime of 100 years and considered some sea-level rise scenarios as well as ecosystem compensation measures (Crémona et al. 2019).

4.2.2 Coastal erosion and shoreline changes

Protection

In the context of coastal erosion and shoreline changes, coastal protection aims at stabilising the coastline at a fixed average position or at least within a defined buffer area. The vast majority of adaptation efforts in the Mediterranean region has consisted in engineering-based approaches, such as groynes and rip-rap (*high confidence*) (Van Rijn, 2011; Pranzini et al. 2015; Jiménez and Valdemoro 2019; El Masry, 2022). The efficiency and costs of these measures depends on the local hydro sedimentary context, and they have created new management issues such as scouring of infrastructures, loss of habitats and recreational value, as reported for example in Egypt and Italy (*high confidence*) (Nourisson et al. 2018; Biondo et al. 2020; Caretta et al. 2022; El Masry, 2022; El Masry et al. 2022; see *Section 1.3*).

Sedimentary accumulation can be enhanced by onshore repeated artificial nourishment of beaches. The potential for offshore nourishment is more limited due to the relatively low energy of beaches. There is evidence that beach nourishment can be applied at small scale without major damage to coastal ecosystems (Danovaro et al. 2018; Vacchi et al. 2020). Yet, the lack of sand resources in the Mediterranean can compromise the efficiency and feasibility of this measure. Specifically, imported sand may not have the same granulometry as those of beaches, resulting either in quicker dispersion of fine sediments or in a decrease of beach amenities if sediments are too coarse or have different colours (*high confidence*) (Pranzini et al. 2018; Bitan and Zviely 2020; Pinto et al. 2020; Asensio-Montesinos et al. 2020; de Schipper et al. 2021). As sea-level rise is accelerating, protection needs against erosion will increase (Sharaan and Udo, 2020), which will put even more pressure on the limited sand resources available and push coastal protection adaptation to its limits (*medium confidence*).

Nature-based solutions consist of leaving space for sediments and ecosystems in order to favour coastal accretion. One emblematic ecosystem offering beach protection services in the Mediterranean is the declining seagrass meadow ecosystem dominated by *Posidonia oceanica*, which form banks at beaches and protects them from erosion (Telesca et al. 2015). Yet, current management practices often consist of removing *Posidonia* banks of dead leaves from the beaches at least during the summer season (Simeone et al. 2022). Posidonia beaches are now often perceived as negative for tourism despite their beach protection value and potential to store carbon, suggesting a paradigm change will be required to develop this solution, in addition to adequate protection of *Posidonia* meadows (Fourqurean et al. 2012; Telesca et al. 2015; Rotini et al. 2020) (*high confidence*). Other nature-based solutions such as the renaturation of the seashores or enhancing river-coast connectivity (Sánchez-Arcilla et al 2022) can receive public support, but their climate-relevance is not always understood, which raises the need for more information of the public (Sauer et al. 2022).

Accommodation

Accommodation options relevant to erosion include measures aiming at sustaining the protection and recreative services of beaches (Jiménez et al. 2011) or changing land use, for example by replacing an agricultural area by a salt marsh (López-Dóriga, and Jiménez 2020; Molina et al. 2020). Accommodation in the context of shoreline erosion requires space and can be combined with nature-based solutions and relocations in order to create a buffer area within which the shoreline can evolve without damages to infrastructure. This option is considered as a potential transformative adaptation coastal approach for example in Egypt (El Masry et al. 2022). The approach requires conserving beaches while accepting some shoreline evolution, which requires implementing setback zones, raising awareness and engaging in participatory approaches with stakeholders (*high confidence*) (Jiménez et al. 2011; Masria et al. 2015; IPCC 2022).

Relocation

Experiments of landward relocation in the Mediterranean region are limited by the lack of space in low-lying coastal areas and by low social and economic feasibility of this option. For example, exploratory studies in France have resulted in only a few implementations such as a 55 million Euros managed realignment on the sandspit between Sètes and Marseillan between 2007 and 2019 (Heurtefeux et al. 2011; Rocle et al. 2021). Another relocation project has been implemented in Slovenia, where the coastal state road from Koper to Izola has been moved inland, and the coastal space is to be reused and rehabilitated (Adriadapt 2022). The lack of implementation of relocation can be due to constraints such as existing infrastructure, population growth and geopolitics (Portman 2012), as well as the lack of perceived urgency, resistance and the complexity of decision making when multiple stakeholders are involved (*medium confidence*) (Dachary-Bernard and Rey-Valette 2019; Rey-Valette et al. 2019).

4.2.3 Coastal ecosystems changes

Autonomous adaptation

Adaptation of Mediterranean coastal ecosystems to climate change takes place in the context of terrestrial and infralittoral habitat fragmentation, destruction, loss and overexploitation of coastal marine resources, severe nutrient loads and pollution and non-indigenous species that arrive mainly through the Suez Canal (IPBES 2018; Kim et al. 2019; Ali et al., 2022; Antunes et al. 2022). In the Mediterranean, autonomous adaptation to climate change is further limited by the impossibility for marine, freshwater and island-terrestrial ecosystems to migrate northward or to higher altitudes to move to more suitable thermal conditions (Ali et al. 2022; Antunes et al. 2022). In this context, limits to autonomous adaptation of endemic species are already reached for diverse groups of marine species, including macroinvertebrates (e.g., Cnidaria, Porifera, Bryozoan), macroalgae, seagrasses and fish species, which have been affected by mass mortality events associated to marine heatwaves (*high confidence*). During the last two decades, the frequency, number of species affected and the severity of impacts have increased, and local extinction events have been observed (Garrabou et al. 2019; Kim et al. 2019; Ali et al., 2022; Garrabou et al. 2022). For example, between 40 and 75% of surveyed marine species were affected by yearly mortality events from 2015 to 2019 in the Western-Mediterranean (Garrabou et al. 2022).

In the coming decades, heatwaves, droughts, salinization, erosion or submergence due to sea-level rise and ocean acidification represent additional threats to beaches, wetlands, lagoons, river, estuarine and marine ecosystems (Lacoue-Labarthe et al. 2016; Parmesan et al. 2022). This raises adaptation challenges for the coastal ecosystems themselves as well as for their associated services, including activities such as fishing and aquaculture (Azzuro et al. 2019; Ali et al. 2022). To respond to this challenge, a range of approaches to support the adaptation of coastal ecosystems has been explored, experimented with, or implemented in the Mediterranean, including measures supporting autonomous adaptation, technologies, innovations (including nature-based solutions), and socio-institutional adaptation.

Measures supporting autonomous adaptation

Autonomous adaptation is supported by habitat protection, limitation of human pressures, and area-based conservation measures. Such measures are implemented in the Mediterranean, but they are too limited in scale and ambition to curb coastal ecosystem losses (*high confidence*) (IPBES 2019; Ali et al. 2022). The effectiveness of current marine protected areas to support coastal marine ecosystem adaptation to climate change is limited due lack of surface areas with high levels of protection (no-take-no-use areas), a lack of representative networks ensuring species connectivity, the absence or poor implementation of management plans and a lack of consideration of climate change in existing plans and MPAs design (Mediterranean MPA Status report MEDPAN 2021; Bednar-Friedl et al. 2022).

Habitat protection measures aiming at reducing eutrophication of coastal and freshwater ecosystems would require strong reduction of nitrogen use in the agriculture sector, a shift toward agro ecology (IPCC 2022), as well as improvements in water treatment plants (Malagó et al. 2019). Protecting Mediterranean lagoon ecosystems more efficiently would require careful ground and surface water management, including demand-reduction measures to limit the degradation or disappearance perennial and intermittent water bodies as well as to restore quality freshwater and sediment inflows (Erostate et al. 2019; Parmesan et al. 2022). Because the implementation of these measures is limited in scale and ambition, limits to autonomous adaptation are being reached for an increasing number of species, habitats and ecosystems (e.g., Mediterranean gorgonians, mussels, seagrass meadows, freshwater ecosystems, wetlands…) (Rodríguez-Santalla et al. 2021; Ali et al., 2022), especially since 2015 for coastal marine ecosystems (Gabarrou et al. 2022). Hard limits are projected to be increasingly reached, especially above 1.5°C Global Warming Levels (Ali et al., 2022).

Technologies and innovation

Technologies and innovations supporting coastal ecosystem adaptation include coastal adaptation measures that consider or benefit coastal ecosystems, as well as active restoration and assisted evolution. While there is evidence that a greener design of coastal protection infrastructures such as groins and breakwaters can benefit to coastal ecosystems (Shoonees et al. 2019), coastal protection measures in the Mediterranean have had damaging impacts to coastal marine freshwater and terrestrial ecosystems so far as they reduce and fragment habitats (Sedano et al. 2021). Hence, future coastal adaptation to sea-level rise risks of flooding and erosion represents a significant threat for Mediterranean coastal ecosystems if coastal engineering approaches do not leave space for sediments and coastal ecosystems (Ali et al. 2022).

Active restoration actions are direct human interventions supporting the recovery of ecosystems that have been degraded, damaged or destroyed. Active restoration is experimented in the Mediterranean, for example, to curb the extensive loss of macroalgal forests or restore coastal wetlands (Mauchamp et al. 2002; Pueyo-Ros et al. 2018; Tamburello et al. 2019). These actions can support a global strategy including also a large reduction of human pressures causing the decline of macroalgal forests (Cebrian et al. 2021). Managed aquifer recharge is another example of active restoration of aquatic ecosystems linked to groundwater as maintaining freshwater resources in coastal areas threatened by salinization due to coastal aquifer overexploitation (Rodríguez-Escales et al. 2018; Dillon et al. 2020). However, the scale and ambition of current ecological restoration is too limited to support the recovery of habitats at relevant ecological scales.

Assisted evolution, which aims to influence the evolutionary trajectory of species, can be beneficial for Mediterranean crops, but its advantages are largely unknown for most Mediterranean wild species (Aurelle et al. 2022). Assisted evolution raises ethical issues and risks and may not be necessary for species with high gene flows or dispersal ability, such as many trees and marine species (Aurelle et al. 2022). However, monitoring of the genetic adaptation of Mediterranean wild species to warming would be useful to assess the potential and limits to autonomous adaptation more precisely.

Socio-institutional adaptation

Socio-institutional adaptation measures supporting ecosystem adaptation include monitoring and educational activities as well as coastal and water management and governance strengthening, monitoring, and mutual exchange of local knowledge (Azzurro et al. 2019). Significant observation and knowledge gaps in the Mediterranean coastal ecosystem prevent creating the conditions for climate-resilient coastal ecosystems along the Mediterranean (Erostate et al. 2020; Vera-Herrera et al. 2022; Soria et al. 2022). For example, better monitoring of pollutants and nutrients that compromise the hydrology of Mediterranean coastal ecosystems such as wetlands and lagoons could support more careful management of agriculture activities and wastewater treatment plants and reduce eutrophication (Soria et al. 2022; Vera-Herrera et al. 2022). Educational activities can support the emergence of a shift toward more ecosystem-friendly practices, avoiding widespread activities such as beach cleaning and trampling that cause dune and intertidal ecosystem declines in the Mediterranean sandy coastlines (Sperandii et al. 2020; Della Bella et al. 2021). Integrated coastal zone management is increasingly considering coastal ecosystems, owing to the implementation of European directives such as the water and marine strategy directives in the north Mediterranean (Bednar-Friedl et al. 2022). This includes increased recognition by the tourism sector that its impacts on the Mediterranean coastal environment can damage itself, and that this sector would benefit from moving toward more sustainable practices (Drius et al. 2019).

Yet, despite these recognitions, the current institutions have not succeeded in establishing a socio-institutional context able to preserve ecosystems so far *(high confidence)* (Said et al. 2018; Erostate et al. 2019; Ruiz-Frau et al. 2019). Strengthening current institutions and governance relevant to at all levels, from local to basin-scale can be beneficial to Mediterranean coastal ecosystem management (Geijzendorffer et al. 2019; Ali et al. 2022). For the preservation of ecosystems, marine conservation science that considers functionality can broaden the scope of what is considered "worth" protecting (Rilov et al. 2020). In addition to areas set aside purposely as marine protected areas, especially those in nearshore coastal waters, areas closed to human uses for reasons other than conservation could be considered. Referred to as Other Effective Conservation Measures (OECMs), actions taken in the past have resulted in areas that could be considered within networks of protected areas (Shabtay et al. 2018, 2019).

4.2.4 Scarcity of coastal freshwater resources

The adaptation needs vary significantly across sub-regions, depending on the hydrogeological and coastal water management context. There is *high confidence* that adaptation to reduced water availability is taking place in the Mediterranean coastal areas. These adaptation options consist of increasing water supply, reducing water demand, improving water quality, and supporting measures and governance (Caretta et al. 2022).

Increasing water supply

Observed adaptation often focuses on increasing water supply, through measures such as water diversion and transfers, diversification of resources, creating surface reservoirs, favouring the retention of water by the soil through adapted agricultural practices, favouring managed aquifer recharge when water is more abundant, water reuse and desalination (Zheng et al. 2021; Ali et al. 2022, Bednar-Friedl 2022). While generally efficient, these measures are already raising significant social, environmental, and economic challenges in the Mediterranean coastal regions (*high confidence*) (Pulido-Bosch et al. 2019; Malago et al. 2021). For example, many wastewater reuse plants lack decarbonized energy production (Malago et al. 2021). Furthermore, the rejected brines from existing desalination plants in the Balearic Islands have adverse impacts on *Posidonia* meadows (Capo et al. 2020). Together with other activities affecting ecosystems negatively such as trawling, this can favour non-indigenous species (*high confidence*) (Kiparisis et al. 2011; Xevgenos et al. 2021). Surface water reservoirs are vulnerable to heavy droughts due to evaporation, and groundwater recharge or water diversion requires investments and a season during which water is more abundant (Vicente-Serrano et al. 2017). Overall, there is evidence that adaptation aiming at increasing water supply in Mediterranean coastal areas is reaching soft to hard limits in many subregions, including the North-Western Mediterranean (Lavrnic et al. 2017; Malek and Verburg, 2018). There is *high confidence* that increasing water supply should be combined with measures aiming at reducing the demand and increasing water quality will be increasingly required to manage water in a sustainable way in the coastal zones of the Mediterranean region (Bednar-Friedl 2022).

Yet, meeting the demand for water, in particular from the agriculture sector, will also require increasing water supply in coastal Mediterranean regions, including through adaptation measures that can receive poor to moderate public support such as wastewater reuse (*medium confidence*) (Lavrnic et al. 2017; Morote et al. 2019; Malagó et al. 2021; Zheng et al. 2021).

Demand-oriented adaptation

There is *high confidence* that adaptation measures aiming at reducing the demand are increasingly needed to address water scarcity in Mediterranean coastal areas. The demand for water can be achieved by improving irrigation, changing agricultural practices, improved urban water management, economic and financial incentives, the regulation of distribution as well as migration or off-farm diversification. There is increasing recognition that these measures, especially those aiming at improving irrigation and reducing the water demand for the agriculture sector, need to be implemented at a much larger scale than now in order to manage Mediterranean coastal water scarcity (Brouziyne et al. 2018; Harmanny et al. 2019; Kourgialas, 2021). For example, it has been estimated that improving irrigation could reduce the water demand by 35% in the Mediterranean region techniques (Ali et al. 2022). However, some agricultural practices are also evolving toward maladaptation lock-ins. For example, avocado cultivation is expanding in the Mediterranean, whereas it is highly vulnerable to salinity and water scarcity, thus increasing adaptation needs (e.g., irrigation improvements, fertigation, precision agriculture) (Mentzafou et al. 2017; Portillo Juan et al. 2022).

Improving water quality

Climate change is projected to decrease coastal water quality in the Mediterranean coastal region due to accumulation of pollutants and nutrients during drought and due to sea-level rise and salinization (Zheng et al. 2021; Caretta et al. 2022). For example, in the Nile Delta, sea-level rise is projected to favour water quality decrease, with adverse impacts for coastal ecosystems and aquaculture, but coastal water management plans able to address the challenge are lacking so far (Shalby et al. 2020). Measures aiming at improving water quality include wastewater treatment, nature-based solutions and change in agricultural practices. Wastewater treatment is implemented, especially in the North-western Mediterranean coastal subregion, but so far with sizable adverse impacts to coastal ecosystems (see *Section 1.3*). Nature-based solutions such as favouring marsh accretion to reduce the surface saltwater inflow into aquifers and estuaries requires space for biophysical processes, and there is *low confidence* that they remain feasible and efficient for high rates of sea-level rise (Zhang et al. 2022). Transformation of the agriculture sector will be required to reduce pollutants and nutrients and limit their impacts for water quality (see *Section 1.3*). In a context of water scarcity due to drought, developing an infrastructure, agricultural practices and ecosystem-based adaptation able to improve water quality can contribute to adaptation efforts but represents a transformative system change (*high confidence*) (IPCC 2022). Such a transformation of the water/agriculture/food nexus can bring substantial co benefits, such as increased human health (Zuccarello et al. 2021), aquaculture easing (El-Mezayen et al. 2018) and healthier terrestrial and freshwater ecosystems (see *Section 4.3*).

Governance

Increasing water availability and improving its quality requires stronger governance, policy, institutions, including transboundary management (Möller et al. 2020), as well as drought early warning systems, climate services, education and training (*high confidence*) (Ali et al. 2022). Yet, strategic and forward-looking planning can address the challenge of coastal water management in the Mediterranean (*low confidence*). Awareness and understanding of the magnitude of impacts is rising but remain limited (Mastrocicco and Colombani 2021). For example, hard adaptation limits are projected to be reached below 3°C of global warming in the Mediterranean coastal regions in the sector of hydroelectric production. Addressing the challenge of water scarcity will require a holistic approach addressing water quality and quantity within the agriculture/food/biodiversity nexus, as well as a willingness to cooperate (*high confidence*) (IPBES 2018; Bednar-Friedl et al. 2022).

4.2.5 Acidification of coastal waters

Acidification of coastal waters is a reason for concern in the Mediterranean region due to its geographical settings and human activities (Range et al. 2014; El Rahman Hassoun et al. 2022). Besides reducing greenhouse gas emissions, regional alkanisation scenarios have been explored, but their impacts on ecosystems remain largely unknown (Butenschön et al. 2021). There is high confidence that stronger governance is needed to address acidification challenges in the Mediterranean region, but a lack of observations and research prevents assessing the feasibility and efficiency of autonomous adaptation of ecosystems (El Rahman Hassoun et al. 2022).

4.3 Pollution

Coastal waters are heavily influenced by pollution originating from numerous human activities, such as industry, agriculture, urbanization, and tourism. These are mainly land-based point and non-point sources which cause the continuous degradation of coastal ecosystems. The Mediterranean Sea is one of the most affected regions and subject to intense pressures related to various types of pollutants that result in altering the physical, chemical, and biological characteristics of its coastal ecosystems. Significant pollutants include substances, such as nutrients (Malago et al. 2019), plastic litter (Llorca et al. 2020), metals (Agamunthu et al. 2019), Persistent Organic Compounds (POCs) (Castro-Jiménez et al. 2021), Polycyclic Aromatic Hydrocarbons (PAHs) and forms of energies, such as thermal, and noise. More than 700 tonnes of plastic waste are discharged in the Mediterranean Sea, municipal solid waste generation has been constantly increasing in the region in the past decade, wastewater treatment plants largely contribute to nitrogen discharges leading to eutrophication phenomena, while the presence of emerging contaminants from pharmaceuticals, cosmetics, retardants, and others, with unknown long-term costs, has been reported (UNEP/MAP and Plan Bleu 2020).

Pollution management is proposed at different levels, but solutions at the source point are usually simpler to implement, long-lasting, and easier to monitor. It is often more cost effective to prevent pollution from being created at its source than to manage it at the endpoint. However, targeting solutions at the source of pollution is not always straightforward, especially considering non-point sources, secondary emits, and/or multi-dispersed origins of pollutants. In general, pollution management focuses on altering the human activity that causes the problem, controlling the release of the pollutant and restoring the damaged systems. Mediterranean countries have committed to depollute the Mediterranean Sea based on the “Horizon 2020 Initiative” under the Euro-Mediterranean Partnership (or the UfM, as it was later re-launched). This overarching objective prioritised management focus on municipal waste, urban wastewater, and industrial emissions (Spiteri et al. 2016), even though current developments seem to overtake these targets. To highlight this, research on solutions at the coastal ecosystem level seem largely under-represented.

As a result of the recent European Green Deal development (COM 2019), the new Circular Economy Action Plan aims to promote changes so that by 2050 Europe becomes more use-resource efficient, with key objective the Municipal Solid Waste (MSW) management, even though this constitutes a very complex task (Kolekar et al. 2016). MSW generally includes fractions of paper, plastic, rubber, fabrics, food waste, wood and yard trimmings, cotton, and leather. These are suitable for the Waste-to-Energy industry towards alternative fuels, and power generation endpoints (Mata-Lima et al. 2021). Ezio et al. (2017) propose that compost can be an ideal treatment to be implemented widely in the South-Eastern Mediterranean region where the organic fraction in MSW is high. Italy is among the top biowaste-generating countries in Europe and is a model paradigm for the rest of the Mediterranean countries to set decentralised composting programs to achieve the action plan targets (Bruni et al. 2020). Compost from MSW has been found to be an alternative nutrient source for agriculture under Mediterranean conditions (Leogrande et al. 2020; de Sosa et al. 2021), contributing to pollutant removal and circular economy, while ethanol production from the cellulosic content of MSW is also proposed (Faraco and Hadar 2011). Extensive research has investigated the potential of treated municipal wastewater for recycling and reuse in the Mediterranean countries, where treated wastewater reuse in agriculture is a common practice and there is a significant interest in the long-term effects of treated wastewater on crops (Pedrero et al. 2010; Saab et al. 2021a,b).

Wastewater

Overall, wastewater constitutes a substantial environmental issue that affects the Mediterranean region. The high organic load with toxic characteristics and low biodegradability of these effluents causes pressure to recipient ecosystems. In particular, the management of Olive Mill Wastes (OMW) has been prioritized to minimise environmental impacts, and olive mills have been obliged to treat or even substantially reduce their wastes. However, there are technical challenges to achieve efficient treatments, since the OMW compounds-rich composition is highly variable, and largely non-biodegradable (Roig et al. 2006; McNamara et al. 2008). The Fenton's process has been examined as a suitable detoxification option for the Mediterranean environment (Domingues et al. 2018). In short, it is based on the production of hydroxyl radicals via the decomposition of hydrogen peroxide by iron ions. Fenton's process can be applied preceding a biological treatment, as the effluents' biodegradability increases while toxicity is reduced.

A novel technology tested in real-scale systems in the Mediterranean is the Microbial Electrochemically Assisted Treatment wetlands that relies on the stimulation of electroactive bacteria to increase the degradability potential of urban wastewater pollutants (Peňacoba-Antona et al. 2022). An alternative proposal consisted of the development of a wastewater storage lagoon, an anaerobic digester, and a landfill disposal system. However, EU directives prohibit wastewater disposal to landfills; thus, controlled application, and appropriate pre-treatment system design towards landfill stabilisation could provide a sustainable solution for urban wastewater effluents dispersed in the Mediterranean region (Diamantis et al. 2013). Other experimental solutions towards wastewater pollutant removal have been recently tested in small scales, such as the use of green roof with different substrates and plant species for greywater treatment (Thomaidi et al. 2022), the use of magnetic particles to reduce phosphorus in treated wastewater (Álvarez-Manzaneda et al. 2021), and the retention of wastewater in seminatural ponds, together with the use of biofilters, to improve the processes of assimilation of nutrients (De-Los-Ríos-Mérida et al. 2021). Yet, treated urban wastewaters in the basin mainly undergo primary and secondary treatment targeted to remove biological oxygen demand, while tertiary technologies are rarely implemented (Frascari et al. 2018).

Industrial discharge

Industrial discharges in the coastal waters of the Mediterranean Sea accounts for approximately 10% of nutrient inputs (UNEP/MAP and Plan Bleu 2020), but industries related to cement, energy, fertiliser, chemicals, and metals production are responsible for high atmospheric metal emissions, which can be deposited to aquatic systems via rainfall or enter coastal sites through basin influxes and run-off (UNEP/MAP/MED POL 2012). Pressures brought by industry to coastal and marine environments add to and interact with other types of pressures, generating a broad range of waste and pollutants. On-site solutions addressing generic waste disposal are limited in the region and mostly are at a small-scale, research level. For example, passive abiotic treatment of acid mine drainage (AMD) with phosphate mining residuals was investigated in a mine in Algeria, indicating that all phosphatic lithologies were efficient in the treatment of AMD, efficiently removing metals by all materials (Merchichi et al. 2022). In another example, the carbon footprint variations were assessed in Spanish dairy cattle farms after modelling different scenarios focusing either on changes in management or changes in the diet of cattle. The management scenarios included the increase in milk production, the change of manure collection systems, the change of manure-type storage method, the change of bedding type, and the installation of an anaerobic digester. On the other hand, changes in feeding strategies included the reduction of the forage concentrate ratio, the improvement of forage quality, and the use of ionophores. Results suggested that changes in management were more effective in reducing greenhouse gas emissions, which can burden coastal recipient systems (Ibidhi and Calsamiglia 2020). In Addition to the above-mentioned industries with straightforward pollution potential, an important contributor to coastal pressures is tourism. The overall flow of tourism in Europe is concentrated on Mediterranean coastal regions and is associated with a high environmental footprint with extreme pressure in the ecosystem and coastal areas (Pirani and Arafat 2014; Zorpas et al. 2018). Today, the implementation of environmental management systems (EMS), such as EMAS, ISO 14001, Green Key, which have been accepted by the tourism industry (Voukkali et al. 2017; Zorpas 2020) promote eco-friendly waste management practices, including waste collection and transportation, specific order requirements from suppliers, and some recycling from stakeholders (Voukkali et al. 2021). However, these practices need modernization, further assessment, and cost-effective corrections.

The management actions described above, albeit in par with the European action plan, can be complex and costly to implement in large scales, and mainly address pollutant inputs at the generic waste level. Thus, solutions applied or tested may overlook specific significant pollutants of coastal ecosystems, including emerging contaminants previously ignored. In accordance with global trends, Mediterranean coastal areas receive excessive loads of nutrients, due to the increased anthropogenic presence, from river fluxes and basin run-offs, aquaculture farms and fertilisers, urban effluents, industrial wastes, and airborne deposition (Karydis and Kitsiou 2012). Nutrient inputs are the key cause leading to eutrophic phenomena with many adverse effects for the marine ecosystem, aquatic life, humans, and economy (Ferreira et al. 2010), which become increasingly pronounced in the last decade around the Mediterranean coasts (Tsikoti and Genitsaris 2021). Environmental indicators towards quantifying eutrophication impacts and water quality (e.g., European WFD 2000/60/EC (EC 2000) have been proposed and developed, although their integration to management strategies is challenging. According to the Nitrates Directive (91/676/EEC,) which aims to reduce nitrates inputs from agricultural sources (EEC 1991b), two management tools are promoted, the assignment of vulnerable and sensitive zones and the development of good agricultural practices, including crop rotation systems, and appropriate procedures for land application that consider the land slope, the period of applying fertilisers, and the proximity of water recipient systems. Ample information and data from monitoring programmes are available in the region, and solutions towards nutrient input reduction are known and implemented globally; but management strategies in the Mediterranean do not seem to suffer from lack of information and policies but rather the implementation of these policies. In general, solutions at the source point are focusing on anthropogenic nutrient input decrease, especially on dual N and P control. Consequently, measures to reduce nutrient pollution consisted of upgrading all waste water treatment plans towards increased nutrient removal by applying enhanced reduction of phosphorus, and lowering the mineral fertilisation in agricultural fields by setting nitrogen surplus limitations without changing the livestock and manure production (Grizzetti et al. 2021). Large-scale management actions on waste water treatment systems and diversions of urban effluents in the South of France have improved the ecological quality of eight eutrophic coastal lagoons close to Montpellier (Leruste et al. 2016). Other mitigation actions have targeted passive restoration practices at the source, such as sewerage networks treatment in estuarine watersheds and cessation of aquaculture (*Malet et al. 2016*). Additional to the above, three strategies were considered for reducing nutrient inputs into the Mar Menor (south-east Spain), the largest hypersaline coastal lagoon of the Mediterranean basin: (i) reducing the leaching of nitrate to the aquifer by improving irrigation routines; (ii) developing of effective tools for denitrification of nitrate-rich brine produced by on-farm desalination plants; and (iii) treating polluted water via hydrologic networks, subsurface flow, and drainage ditches (Álvarez-Rogel et al. 2020).

Plastic Litter

The Mediterranean Sea is recognized as one of the sixth largest marine litter accumulation zones worldwide (Lebreton et al. 2012; Suaria et al. 2016; Fossi et al. 2020). Due to its semi-enclosed shape and its thermohaline circulation of only deep water leaving the basin, the exchange of water with the Atlantic Ocean is limited (Lebreton et al. 2012; Simon-Sánchez et al. 2022). In addition, a heavily populated coastline with highly developed coastal tourism and intense economic activity (30% of global marine shipping traffic) lead to approximately 17,600 metric tons of plastic litter entering the Mediterranean waters annually (Cozar Cabañas et al. 2015; Suaria et al. 2016). The impacts of this pollution are not yet fully understood, but marine litter arguably constitutes one of the most complex challenges of the Mediterranean region (Suaria et al. 2016; Fossi et al. 2020).

Due to its geographical location between three neighbouring continents, there is still no consistent approach to reduce plastic litter pollution, as the gap between politics, science and society still complicates the joint design and implementation of effective mitigation measures (Gorjanc et al. 2020; Cantasano 2022). On European level, the Marine Strategy Framework Directive (2008/56/EC, hereafter referred to as MSFD) was initiated to develop uniform monitoring and mitigation strategies for oceans and seas within the EU, in order to achieve a Good Environmental Status by 2020 (hereafter referred to as GES, Fortibuoni et al. 2021). The MSFD is described by means of target-linked descriptors, whereof three of the descriptors are related to marine litter (Morseletto 2020). These targets include actions such as implementing waste prevention through law-enforcement (such as the EU-ban on single-used-plastic items from 2021), appropriate waste management, such as measures to avoid marine litter generation as well as monitoring measures to control or track the effectiveness of the actions implemented (Gorjanc et al. 2020; Morseletto 2020). Similarly, there are aspects such as governance responses like specific waste management practices, control systems and a circular economy (Morseletto 2020; Fytianos et al. 2021). Even if the GES could not be achieved by 2020 in the Mediterranean region, initial implementation attempts by the MSFD have filled existing knowledge gaps concerning for example beach litter densities and composition (Fortibuoni et al. 2021). As a result, the understanding of the litter problem in the Mediterranean region has increased continuously, due to a wide range of studies driven by the MSFD, the Barcelona Convention Plan for Marine Litter Management in the Mediterranean and the Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast (IMAP) (Morseletto 2020). The latter has fostered the cooperation of all Mediterranean member states since 2016, however as to date most information on marine litter in the Mediterranean Sea remains spatially inconsistent and focused mainly on the north-western part of the Mediterranean Sea (Llorca et al. 2020; Fortibuoni et al. 2021). A first step in addressing this issue be the project Marine Litter MED II initiated by the European Commission (project duration 2020–2023) with a particular focus on southern Mediterranean countries (UNEP 2022). Acting together, all parties could contribute to effectively fostering preventative and reduction interventions, technological solutions as well as education and awareness-raising measures, in order to overcome existing knowledge gaps and support effective decision-making in the future (Fossi et al. 2020; Simon-Sánchez et al. 2022).

Metal pollution of coastal sediments

Although extensive research has been published on metals enrichment of coastal sediments in the Mediterranean (e.g., Okbah et al. 2014; Nour et al. 2017; Martínez-Guijarro et al. 2019; Stamatis et al. 2019), solutions at the source points are not yet well formulated. Sediments act as storage pools that recycle toxic substances to the water column with severe ecotoxicological effects on aquatic species (Lamicelli et al. 2015). To reduce inputs, the introduction of constructed wetlands (CWs) between sources and natural aquatic recipient systems is a proposed approach for eco-remediation in the Mediterranean basin. The role of plant composition of CWs for metals' uptake has raised lengthy debates with contradictory outputs that influence management choices (Guittonny-Philippe et al. 2014). For example, different modules of CW consist of a biotic network in which variable community levels, from microbes to macrophytes and plants, interact and form a depurative ecosystem. This ecosystem must be designed in their substrate and biological composition to address pollution by a specific group of metal contaminants. The selection and management of the biotic counterparts (e.g., cutting and harvest of plants, replanting, frequency and timing of interventions) may affect the efficiency of metal removal choices (Guittonny-Philippe et al. 2014). In addition, biochar has been found to reduce the leaching of heavy metals present in raw sewage sludge in Mediterranean soils, and subsequently positively affect run-off inputs to coastal sites (Méndez et al. 2012). Further concerns have been recently raised about the occurrence, transport and fate of POCs in coastal systems (e.g., Barón et al. 2014; Lorenzo et al. 2019).

Some of the POCs with increased concentrations in the Mediterranean that solutions are investigated include Organophosphate Flame Retardants (OPFRs), Perfluoroalkyl Substances (PFASs), and Perfluorinated Compounds (PFCs). For example, certain OPFRs were degraded by UV, Hydrogen Peroxide (H_2O_2) and Ozone (O_3), while others were resistant to both secondary and tertiary treatments (Cristale et al. 2016). Concerning PFASs, studies indicated that modern wastewater treatments cannot efficiently remove these compounds for various reasons, such as the presence of PFAS precursors. Mainly two mechanisms have been developed for PFAS remediation: separation-concentration and destruction, but the most promising approach is adsorption as being most affordable. However, these mechanisms are not yet ready for full scale application (Vo et al. 2020) and have not been used in Mediterranean paradigms. PFCs are considered emerging pollutants within POCs and are used in several household applications but are not biodegradable and tend to accumulate to sludge with conventional wastewater treatments (Ahrens 2011), entering the environment directly or via the degradation of precursor compounds (Prevedouros et al. 2006). Tertiary treatment with membranes, activated carbon and advanced oxidation processes can be used against these recalcitrant pollutants. Investigation of the distribution and fate of PFCs in Spanish sewage treatment plants has confirmed that removal efficiencies with conventional methods can only partially eliminate these substances (Campo et al. 2014). On the other hand, attention to PAHs, as emerging pollutants in the Mediterranean, is given after new legislation led to the instalment of exhaust gas cleaning systems (EGCSs) known as scrubbers in the systems of the engine and boiler in commercial ships. After scrubbing, a waste stream (scrubber water) containing high concentrations of potentially toxic organic compounds for aquatic life, such as PAHs and metals, is generated and discharged into the marine environment (Tran, 2017). Thus, considering that the Mediterranean Sea is one of the busiest areas with heavy ship traffic, researchers are trying to decipher potential ecotoxicological effects of scrubbers to various levels of biocommunities, from planktonic microbes (Ytreberg et al. 2021) to mussels (Pittura et al. 2018) and fish (Santana et al. 2018). Of course, conventional sources of PAHs, such as agricultural, industrial, and domestic activities, as well as atmospheric transport, have been previously identified. The solutions that can be implemented are targeting mainly conventional sources and include generic waste treatment approaches, similar to those mentioned above. Further research is underway to develop pipelines that involve the biodegradation of PAHs in scrubbers (e.g., see Ismail et al. 2022 for a review).

The above discussion focuses on solutions to reduce pollutant inputs in Mediterranean coasts at the source point, targeting basin and urban sources. Such measures are generally easier to implement having clear goals, they are less costly, more effective, long-lasting, and easier to monitor. Thus, strategies on pollution management at the recipient systems are challenging and have been limited up until now. A first step is the development of quality assessments (e.g., development of appropriate ecological indices) of coastal waters within the scope of the European Marine Strategy Framework Directive (MSFD-2008/56EC), using integrated approaches combining physical, chemical, and biological elements of the ecosystems. Then, when suppression of the causative pressure at the source is insufficient for regime shifts, active restoration by additional management measures based on direct interventions should be employed. For example, for the restoration of seven coastal lagoons in Southern France, plans included attempts to restore seagrass meadows with actively planting or seeding and subsequently harvesting their biomass, which stores excessive nutrients. Macroalgal growth can accelerate the decrease of total N and P contents, provided that its biomass is exported from the lagoon (De Wit et al. 2015). Overall, macrophyte and angiosperm transplants in coastal sites are a frequent and effective strategy to reduce external nutrient loading. During 4 years of plant transplantations at the Venice Lagoon in 32 stations, extensive meadows were formed on a surface of approximately 10 km^2 and a rapid recovery of the ecological status of the involved areas was observed (Sfriso et al. 2021). Similarly, wetland plants promote soil metal adsorption through soil oxygenation. The angiosperm *Paspalum distichum* was found to be a potential phytoremediator of water metal pollution in mesocosm-field experiments in a newly established restored marsh in Ebro Delta (Spain), highlighting the utility of restored marshes as metal filters in coastal Mediterranean systems. However, this bottom-up approach of nutrient-metal loading management often does not match with community recovery, thus restoration is likely not apparent (Duarte et al. 2009). So top-down approaches that target the eutrophication results, that is the development of Harmful Algal Blooms (HABs), have been in theory examined with the proposal to test filter-feeder species farming being qualified (Petersen et al. 2014); but these are not applied in large scales in the Mediterranean region yet, due to associated bottlenecks of shellfish farming which impair the beneficial effects on nutrient harvesting (Stadmark and Conley, 2011).

4.4 Non-indigenous species

Climate change and fragmentation have been two of the major reasons for loss of biodiversity throughout the world, and in the Mediterranean area as well. Warmer conditions, increased salinity, acidity and in some cases pollution (*Ozer et al. 2022*) encourage non-indigenous species in terrestrial, marine and coastal environments of the Mediterranean. Even in the oligotrophic Eastern marine areas, this trend is clear. The telluric, marine and coastal non-indigenous species that have taken hold since climate change effects are salient has led to the current high-risk status. The Mediterranean is the most tourist–dependent region in the world (Lacoue-Labarthe 2016). Risks are related to loss of endemic species whose niches have been overtaken, risks to infrastructure (e.g., power and desalination plants), and sectoral risks, such as food cultivation and loss of recreational values based on existing ecosystems.

In Cyprus, for example, the invasive puffer fish *Lagocephalus sceleratus* (Tetraodontidae) is now outcompeting native fish and their prey, such as the *Octopus vulgaris* (Octopodidae) and squid, which are becoming increasingly scarce (Nader et al. 2012).

Research in the Iberian Peninsula has shown that increased frequency and/or intensity of climate extreme events associated with ongoing climate change are projected to reduce overall invasion risk for the species examined although increases in favorability should be expected locally (Baquero et al. 2021). For aquatic environments, acidification and temperature change (warming) cause increasing risks from non-indigenous species. Throughout the Mediterranean these risks cause significant stress for sensitive species, ecosystems and promote hardy non-indigenous species of flora and fauna (Lacoue-Labarthe 2016).

In the Adriatic Sea research done on the effects of on-going marine sprawl, principally the building of protective infrastructures along coastlines to prevent their change from erosion and accretion processes as well as for anthropogenic needs, has led to the loss of habitats and local biodiversity.

While there are some advantages to these areas in terms of habitat replacement and corridors of relatively stable surfaces, the research has found that habitat for non-indigenous species is more common than development or restoration for natives (*Airoldi et al. 2017*).

One of the local changes occurs in lakes and involves an expanding species not necessarily unknown in the area, but now becoming overly dominant. The magnitude of the projected temperature increases is sufficient to determine significant variations in the growth rate of phytoplankton populations. In a range of temperature between 15°C and 25°C. Oberhaus et al. (2007) measured an increase of threefold in the growth rate (from about 0.15 to 0.45 day^{-1}) of *Planktothrix rubescens* a filamentous and potentially toxic cyanobacterium which is recently invading many European lakes, jeopardising the use of the water resource, especially for drinking supply and bathing (Legnani et al. 2005; Manganelli et al. 2010). In recent years *P. rubescens* has become the dominant species in both Lake Como and Pusiano (Buzzi 2002). The success of this species in the following season is influenced by the autumnal population size (inoculum) whose strength affects the probability to overcome the winter season (Salmaso 2000). Although changes in the phenology of a species are mediated by a variety of factors (such as nutrient availability, water renewal time, light penetration, interspecific competition and predation) the rapid rate of dispersal of this species suggests the presence of global causes. One of these can be reasonably identified in the change of the lake temperature patterns.

Vegetation invasive species found in the Balkan Peninsula (Adriatic-Ionian region) related to habitat fragmentation and climate change of the last two decades are: common milkweed (*Asclepias syriaca*), Jerusalem artichoke (*Helianthus tuberosus*), Japanese knotweed (*Reynoutria japonica*) Bohemian knotweed (*Reynoutria bohemica*), giant hogweed (*Heracleum mantegazzianum*), giant goldenrod (*Solidago gigantea*), Canadian goldenrod (*Solidago canadensis*), and Bermuda buttercup (*Oxalis pes-caprae*) (Gazoulis et al. 2022).

The non-indegenous jellyfish (*Rhopilema nomadica*) has benefited from climate change effects (warmer water) and negatively impacted both tourism and infrastructure by polluting waters and clogging desalination and power plants. It is known that non-indigenious species have a better hold in areas where ecosystems are already stressed (*high confidence*). This is often the situation near desalination plants where there is some evidence that *Posidonia meadows* are affected by brine outfall and fishing practices such as trawling where Lessepsian migrations have taken hold (Kiparisis et al. 2011; Xevgenos et al. 2021).

While these problems and more are observed throughout the Mediterranean region, few adaptation measures have advanced and these are in few locations. The two most common are reduction of non-indigenous species through 1) eradication initiatives; 2) commercial efforts to develop new means of using the abundance of some of these organisms; 3) tailoring of planning and development to encourage and protect native species.

Solutions

There are not many successful adaptations to increasing colonisation and expansion of non-indigenous species such as the Rose-ringed parakeet, the Indian Grey Crow and the Lion fish. Improved planning and construction of marine infrastructures and even marine "urbanisation" can be developed so as to provide habitat and ecosystem services. Climate change impacts such as sea level rise and greater and more frequent storm action can be countered by such approaches (Dafforn et al. 2015). Many of the 1000 non-indigenous species recorded so far have been found in the eastern Mediterranean and are detrimental to fisheries but some are now targeted commercially (Lacoue-Labarthe 2016).

As said, tailoring of development and planning to encourage native species includes the establishment of protected areas that would allow ecological connectivity (to counter habitat fragmentation) for endemic and local species. A total of 39 Specially Protected Areas of

Mediterranean Importance (SPAMIs) are listed under the Barcelona Convention. Much more attention to moving forward with the official recognition of these SPAMIs is needed. This attention needs to include many different kinds of actions from providing some kind of regulatory protection to these areas to even simply raising awareness of their existence and importance. There is strong evidence (*high confidence*) that most of the protected area in the Mediterranean Sea is under strain from variable climate change and that this is detrimental to native biota (Kyprioti 2021).

A critical look at extractive practices, as these gain traction due to neoliberal narratives favouring profit accumulation at the expense of social and environmental sustainability, is also lacking, especially in academic circles, professional training programs and government (public sector) ministries and authorities. Emphasis on economic incentives to reduce the use of non-indigenous species, for example in public spaces could be adopted by states and regions who then offer economic incentives to local municipalities and even NGOs.

Lastly, further research is needed to understand how climate change effects are driving various interactions. For example, the increase in the need for clean drinking water has caused an increased reliance on desalination, especially in tourist destinations.

4.5 Risk synergies and management considerations

A further challenge for managing coastal risks, which is generally overlooked when preparing for coping with climatic and environmental risks, is the interaction of different processes at different temporal or spatial scales (Zcheischler et al. 2018). These interactions can result from drivers that occur simultaneously or in succession and whose direct impacts overlap, spatially and temporally. Such events have been termed as consecutive events or disasters and include a broad range of multi-hazard types, such as compound and cascading events (see de Ruiter et al. 2020).

The Mediterranean appears to have a high potential for the development of different types of consecutive events. Examples include the north-western coast, which is experiencing the highest compound flooding probability in Europe (Bevacqua et al. 2019); the Iberian Peninsula, northern Italy, northern Africa, and the Balkans, which have been identified as the main hotspots where the occurrence of drought events in the spring or early summer could lead to extremely hot temperatures in the summer (Russo et al. 2019); the significant increase in the number of compound warm spells and droughts in the entire Mediterranean Basin over the last 40 years, particularly in late spring, with the increase being attributed to temperature rise rather than lack of rainfall (Vogel et al. 2021); and the co-occurrence of daily rainfall extremes along the crest line of the Massif Central in the French Mediterranean region (Blanchet and Creutin 2017). Future projections indicate that the probability of such events may increase; Ruffault et al. (2018) found that increasing drought conditions projected by climate change scenarios could affect the dryness of fuel compartments and lead to a higher frequency of extreme wildfire events. Wildfires may in turn lead to elevated organic carbon, iron, and particles, which are eventually discharged into the ocean affecting coastal chemistry and even leading to a decline in coastal habitats and their functions (Herbert-Read et al. 2022).

4.5.1 Managing the risks of consecutive events

Consecutive events are not considered in the planning of responses to risks, which can lead to serious issues: first, the sequential occurrence of each event and the amount of time between two disasters can substantially affect the vulnerability to the next hazard (de Ruiter et al. 2020); second, solutions aiming at reducing the impacts of single drivers (e.g., coastal flooding) may exacerbate the effects of the compounding driver (e.g., pluvial flooding), thus rendering any prevention measures inadequate for their purpose and leading to maladaptation.

Limited scientific understanding of consecutive events and in particular their spatial and temporal dynamics, is one of the main barriers to managing the risks of these events. Further multi-hazard assessments that account not only for consecutive risks but also for the planning of specific measures are essential as wrong decisions for adapting to consecutive events can considerably exacerbate risks to infrastructure and human life. Last, as these hazards are dynamic in nature (de Ruiter et al. 2020) and can cross national boundaries, establishing international cooperation between Mediterranean states in disaster response is essential for managing risks.

Tsunami

Given the tsunami threat existing in the Mediterranean region (see *Chapter 3*), the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS) was formed in response to the tragic tsunami in the Indian Ocean on 26 December 2004. The Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) received a mandate from the international community (June 2005) to coordinate and to develop a Tsunami Early Warning System for the region. This is the NEAMTWS (North-Eastern Atlantic, Mediterranean, and Connected Seas Tsunami Warning Systems). The guidelines for the NEAMTWS activities are compiled in the NEAMTWS Implementation Plan. (http://www.ioc-tsunami.org/index.php?option=com_content&view=article&id=10&Itemid=14&lang=en)

At present, five institutions in the tsunami community act as accredited Tsunami Service Providers (TSP) as part of the regional system in the NEAMTWS, namely NOA (Greece), INGV (Italy), CENALT (France), KOERI (Türkiye) and IPMA (Portugal). Furthermore, additional institutions participate in National Tsunami Warning Systems (NTWS) (e.g., in Spain and Romania). The TSPs and NTWSs are also involved in national contingency planning for tsunamis, with hazard and risk mapping. This necessitates a strong link and continuous interaction with civil protection agencies and local authorities responsible for the implementation of local emergency plans. Such interactions have included hazard mapping and evacuation planning.

There is currently a growing consideration of tsunami risk in the region, in which UNESCO is playing a major role, in encouraging, and supporting the preparedness of exposed coastal communities through different means. Among others, these include promoting the maintenance of JRC-IDSL devices (tide gauges), and encouraging, the implementation of the Tsunami Ready international recognition programme for municipalities in the NEAM region. The Tsunami Ready Recognition Programme is an international community-based recognition programme developed by (IOC-UNESCO). It aims to build resilient communities through awareness and preparedness strategies that will protect life, livelihoods and property from tsunamis in different regions.

4.5.2 Residual risks

Hazards will inevitably lead to residual loss and damage, despite any adaptation or mitigation measures that will be undertaken. Identifying the response limits of societies and ecosystems is challenging as these limits dynamically evolve in physical and socioeconomic systems with time. Reimann et al. (2018) for example, identified increasing residual risks for the Mediterranean coasts under SSP5, due to the high concentration of population and assets in the coastal zone.

Residual risks are not quantified or even identified for the Mediterranean coastal regions, largely also due to limited knowledge on the actual response needs to the different hazards. Understanding residual risk is a key element of adaptation policies, particularly in a rapidly developing coastal environment where future risk will concentrate on areas that are currently experiencing low or no risk. As Mediterranean nations are increasingly in a position to shape their future coastline, managing residual risk needs to be a primary consideration in this process.

4.6 Barriers to effective responses

Responses to coastal risks are often hampered by different factors. Such factors include technical, economic and management barriers (Sánchez-Arcilla et al. 2022), governance barriers, stakeholder perceptions (Clément et al. 2015) or barriers related to financing coastal adaptation or to social conflicts induced by adaptation processes (Hinkel et al. 2018).

Due to the geographically diverse socio-economic settings and the lack of a tradition of coastal adaptation along large parts of the basin, adaptation to coastal risks in the Mediterranean faces different types of barriers. For example, Hinkel et al (2018) find that the Catalan coastal zone coast does not currently face major technological, financial or economic barriers and that social conflict can be the main impediment in coastal adaptation. Work on the perceptions of responses related to issues such as retreat, erosion and loss of ecosystem services due to sea level rise in the Mediterranean coastal zone (e.g., in France, Clément et al. 2015; and in Greece, Tourlioti et al. 2021) indicates differences in perceptions regarding financing of coastal adaptation and compensation of damages. At the same time Schleyer-Lindermann et al. (2022) identify an optimism bias in a case study for the cities of Marseille and Nice (France), whereby people are aware of climate change but appear not to worry about it. Such perceptions may be related to the lack of specialised and tailored information on risks related for example to sea-level rise and specifically the lack of coastal climate services (Le Cozannet et al. 2017), or to the lack of risk assessments for major population or commercial centers, as for example in port cities (Valente and Veloso-Gomes, 2019). Such information would facilitate the incorporation of adaptation considerations into planning and would potentially mobilise public support regarding the need of adaptation to coastal risks. Last, prioritising the implementation of the existing legislation, namely the ICZM protocol, which is currently impeded by these and other factors, would be a substantial step towards overcoming barriers and promoting effective responses.

4.7 Science-policy interface

4.7.1 Defining science needed for policy making in the times of climate emergency

In the ICZM scientific literature, two traditions related to the science-policy interface can be distinguished; one that understands science in its traditional form, and one that embraces a participatory interface, which includes multiple knowledge systems, such as local, indigenous and traditional knowledge. This approach of “open science” (UNEP 2021) is proposed for the Mediterranean. In line with the findings of the post-normal science, or science for policy 2.0 (Jasanoff 1987; Funtowicz and Ravetz 1993; Nowotny et al. 2001) an interdisciplinary approach is crucial and social sciences should be better brought into play. The separation of social sciences and humanities from natural, medical and technical sciences is hugely counterproductive and may lead to many mistakes in policy decisions (*Shucha and Dewar 2021*) state. The idea that the sciences are value-free has long played a key role in the self-understanding and the public image of modern science (Lacey 1999). However, this idea has been recently much contested in feminism, social constructivism, deep ecology, and a number of third world and indigenous people’s outlooks. Humanities, in particular philosophy and sociology, may provide valuable support in decision-making. Philosophy, which deals with morality, ethics, truism or altruism, not only with the theory but also with its skills and virtues (Chislenko 2022), can guide us towards a new paradigm for systemic transition to sustainability.

Modern society is not really designed to make science and policymakers collaborate. Cultural divisions between science and policy can be so large that any fruitful collaboration among them requires major adaptations from both sides (Sienkiewiz and Mair, 2020). Their practical modes of operation, including a lack of flexibility to move beyond, pose a threat to successful evidence-informed policy making, even despite a plentiful supply and demand of knowledge. Mutual adjusting of norms and expectations can only be achieved through dialogue, relationships and mutual learning. Scientists face busy academic schedules and high publishing demands with little incentive for applied science or time to get involved in actual issues (Choi et al. 2005). Policymakers are facing the reality of continuous crisis management, the continuous need to find compromises and to satisfy numerous requirements. The fruitful collaboration of the two groups would need a different framework, designed to overcome all the differences and divisions.

Still in 2013, Bremer and Glavovic reviewed the evolution in the theory and practice of the science-policy interface for ICM, and argued that in the future, the interface should be framed as a “governance setting”. As PAP/RAC elaborated (PAP/RAC 2021) given the complexity of the challenges caused by climate change, science needs to be at the centre of the governance setting. Strengthening governance for climate action is a task that goes beyond the management structures established by the state, whereas its successful implementation requires a broad social partnership. Governance setting should enable co-creation, as defined by Sienkiewiz and Mair (2020) – interlinked collaborative approaches aimed at increasing dialogue, trust, understanding of needs and diversity of input, can increase the importance and impact of evidence for the benefit of public policies.

4.7.2 Two worlds – science and policy making: barriers, obstacles, needs, opportunities

Science-policy collaboration is not an easy task. Although, both of these professions fall into the domain of the public sector jobs, they may be among the most different ones. As Choi et al. (2005) defined differences lie in goals, values, time span, theme span, up to accountability. While the goal of policy makers is to realise their vision through keeping and gaining the support of the voters, the goal of the scientist is to advance science through revealing the truth. To gain or retain the support of the community, policy makers must understand the reality of wide segments of the population related to many possible relevant issues. For scientists, in order to advance in his/her job, which is to reveal the truth, the research issue must be defined as precisely as possible. In this manner, the policymaker must think about “everything” and therefore stay on the surface of the themes, while scientists go very deep into the topic of their research. While a policymaker’s time horizon depends on the approval of the community (voters), therefore mostly able to count on one political cycle at a time (or less), the time horizon of the scientist is focused on one human lifetime. This is probably the biggest difference between the two. Due to the time and themes span, policy makers do not have the luxury of time to dedicate to any particular issue. These two spans are also the reason while these two groups hold to different values and speak different languages.

Finally, while scientists are accountable to their peers and editors, policy makers are accountable to political parties, governments, taxpayers and to their voters. While the scientist’s bad result leads to no publishing for policy makers, bad results may lead to the end of their career. These differences hinder the creation of trustworthy relationships, which are of key importance in sensitive and dynamic policy environments. If we agree that trust is a direct function of understanding of needs, the relevance of support, reliability and quality of human relationships, as Choi et al. states, than governance setting for science-policy collaboration must consider all of the above-mentioned issues. A framework for permanent collaboration and co-creation can enable the inclusion of all sciences and all types of knowledge and secure transparent, relevant and efficient science communication. New approaches to communicating climate science beyond academia are necessary for enhancing salience, understanding, and engagement and accelerating action (Howarth et al. 2020). As they claim, this includes harnessing the value of work in psychology, geography, sociology, and other disciplines in an active, as well as descriptive, sense. By increasing understanding, two groups could increase mutual respect and trust, while the community could improve its climate literacy so that policy makers become accountable to climate literate voters.

4.7.3 Possible solutions: how to bring science closer to the policy makers, how to enable policy makers to use science

The role of science and knowledge is without doubt central for overall systemic transformation of our society towards sustainability – the only way forward to avoid rather catastrophic consequences of climate change. However, as elaborated above, science mostly deals with the issues differently, in its own time, out of the context of fast – modern societies. According to Parkhurst (2016), regarding science – although the overall scientific production is rich and potentially relevant for policy – only a fraction of it will become evidence usable for a particular policy decision. The arguments for such a statement, according to him, lie in the fact that good evidence for policy needs to fulfil three criteria to be appropriate for the specific policy in question:

- Address the policy concern at hand, instead of any loosely related topic;
- Be constructed in ways useful to address policy concern, methodologically able to answer the questions at hand;
- Be applicable to a local policy context.

All of the above could be established in the process of preparation of an adaptation or risk management plan. Analysis that needs to be performed for the plan preparation requires robust quantitative data and results that scientists can produce for policy needs. However, in cases when there is no sufficient data, or no sufficient time or resources, providing scientists, or experts, or expert group opinions can still improve decision-making and planning, in particular having in mind the huge uncertainty dimension of changing climate.

Sienkiewiz and Mair (2020) claim that bridging science and policy closer together can be achieved by engaging them in co-creation at all stages of policymaking, as well as in evidence-making. Co-creation manifests itself in different aspects of the development of science for policy (e.g., co-creation of the research question, of evidence base, of anticipatory knowledge strategies, co-creation through collaboration with stakeholders or citizens, and through the participation of scientists in the whole of policymaking. Since 2013, development and adoption of national strategies and regional and local coastal plans have been supported and advocated by PAP/RAC, as requested by the Protocol on ICZM. The analysis needed for the preparation of the plans represents an opportunity for co-creation for scientists and policymakers. In addition, the process of plan preparation represents an opportunity for the creation of permanent structures for science-policy-community collaboration.

From the listed above it is clear that some new forms of a science-policy interface should be secured at the local and supra-local levels where it can relate to the policy concern at hand. Quality collaboration between scientists and policymakers cannot be casual or occasional; it must be established in a permanent and systematic manner since good evidence needs time and scientific devotion to the questions at hand. Therefore, the new interface requires new principles for institutional practices and some new institutional forms.

The science-policy interface should be a central part of the modern governance setting. Due to the complexity and uncertainty that climate change is bringing, we need science and knowledge to lead the way. Strengthening governance for climate action may be realised by the creation of bodies whose primary activity will be identifying and prioritising climate action while securing vertical and horizontal integration and transfer of knowledge and experiences. Such bodies should present a platform for cooperation between science and policy makers, and act as an anchor that will help climate action to have continuity after political changes in the governing structures (PAP/RAC 2021). The establishment of such bodies, including advisory councils, boards represents examples of innovating governance models. Having local and regional scientists permanently collaborating with local and regional policymakers as members of such bodies could enable timely involvement of the scientists in the relevant policy concern at hand. The establishment of such bodies is part of management measures foreseen within the coastal plans in Croatia. Coastal plan for Split-Dalmatia County within the management measures established the advisory board for coastal management with the representatives of science, businesses and civil society. Setting the methodology for answering the policy concerns at hand, but keeping the transparent long term prospective, such as for example adaptation pathways method (Haasnoot et al. 2013), could help bridge the time divide. Ensuring transparency of scientific advice could help educate climate literate and aware voters while protecting the credibility of the scientists.

A large share of the decisions related to the coast is taken on the local level, and as Parkhurst highlighted, science should be applicable to a local policy context. Instead of continuous increase of build-up in the narrow coastal belt in almost all Mediterranean countries, (PAP/RAC 2017) a setback zone with no construction should be established. In many coastal areas, spatial plans will have to be adapted to accommodate the sea-level rise. High opposition is to be expected; therefore, governance setting should help for increasing awareness, informing and educating the population. A particularly demanding level of trust will be needed for managed retreat, one of the adaptation strategies, which will surely be needed for many low-lying coastal zones. Far reaching decisions, such as managed retreat, should be taken far in advance in order to enable stakeholders and coastal communities to take long term decisions and plan their lives; accordingly, just as it was done in the UK for the case of Fairbourne. Rocle et al. (2021) presented the French experience and showed that multi-level governance processes contribute to the production of "actionable knowledge" for relocation in terms of legitimacy, credibility, applicability and acceptability. The French experience is of a great value to the Mediterranean countries.

4.7.4 Examples in the Mediterranean

In the Mediterranean, there is a long tradition of science-policy collaboration through the Mediterranean Action Plan (MAP), first one of the Regional Sea Programmes of the UNEP. In 1975 the Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean was developed, and with its 7 Protocols it provides a framework for collaboration for all Mediterranean countries. In this framework, many projects have been implemented within which collaboration between scientists, experts and decision makers, as well as civil society and the private sector has been realised. Since 2016 Mediterranean countries have adopted the Mediterranean Strategy for Sustainable Development, a strategic guiding document for all stakeholders and partners to translate the 2030 Agenda for Sustainable Development at the regional, sub-regional and national level. The same year, the Mediterranean countries approved the Regional Climate Change Adaptation framework for the Mediterranean Marine and Coastal Areas.

In 2008 the UfM was created, an intergovernmental institution bringing together all 27 EU countries and the 15 countries of the south and east Mediterranean. In 2014, UfM established its Climate Change Expert Group, whose role is to advance the discussion on climate change priority actions and accelerate the identification and development of concrete projects and initiatives.

Finally, in 2015 the MedECC was launched, and today it operates as an open and independent network of more than 400 scientists working towards a regional science-policy interface for climatic and other environmental changes across the Mediterranean. MedECC is supported by Plan Bleu (UNEP/MAP) and by UfM through the funding of the Swedish International Development Cooperation Agency (SIDA).

All above listed represent the science-policy interface at the Mediterranean level through the network of national governments.

In Italy there is a scientific network National Research Group for Coastal Environment issues (GNRAC), founded in 2006 with the objective to promote and disseminate studies on the status, conservation and management of Italian coasts. The group was founded by the experts with long experience in Italian research projects on coastal issues, and today it has more than 250 members, researchers, local administrators, and professionals in the fields of geology, engineering, geography, ecology and spatial planning. This group has been organising summer schools, scientific field trips, workshops and conferences. It has its scientific peer reviewed journal – Studi Costieri, and during pandemic times organised a series of webinars. GNRAC has become a recognised expert hub for coastal issues in Italy. However, in this case, the connection with policy makers is only marginal and occasional. Such networks represent a great value to society and should be connected with the policies in a formal and structured manner.

As highlighted by PAP/RAC (PAP/RAC 2020) governance, at its core, is made of various boards and councils because through them is the easiest to link governance with management. Examples of Advisory bodies are presented below.

The Academic Advisory Board for the Barcelona 2030 Agenda is an advisory and consultancy body made up of outstanding members of Barcelona's academic community. Some of its functions are to advise Barcelona City Council's governing team on the development of the 2030 Agenda and the achievement of the SDGs in the city; To promote the undertaking of studies with universities, schools and colleges, research centres, companies, foundations and public and private institutions; to propose actions/projects with the objective of making Barcelona a benchmark city in the fulfilment of the SDGs and to put forward innovative public policies to achieve these objectives; to have a broad overview of all aspects related to the 2030 Agenda, especially in relation to the actions, initiatives and projects promoted by the City Council; and to promote citizen knowledge and support regarding the 2030 Agenda and the SDGs, amalgamating the academic world, schools and citizens. This Advisory Board has its working group on climate change and few thematic reports available on their website. (https://ajuntament.barcelona.cat/agenda2030/en/who-we-are/academic-advisory-board-barcelona-2030-agenda). Such a body could represent an entry point into science-policy interface, in particular if it collaborates with the commission for promoting the achievement of the 2030 Agenda, another body of Barcelona created to align municipal policies with the SDGs, to measure and analyse the evolution of the city with respect to the SDGs and to promote the collaboration required to advance their achievement. However, their collaboration should be on a permanent basis, and for now, this body is meeting only twice a year.

The Advisory Board for integrated planning and management of coastal and marine areas of the Split–Dalmatia County in Croatia is part of the governance mechanism established with the Coastal Plan for Split–Dalmatia County. This plan has been developed from 2019–2021 and adopted in the County Assembly in September 2021. The Plan was initiated by the County Department for maritime affairs and tourism and one of its priorities is adaptation to climate change. Members of the Advisory Board are the representatives of the University, Institutes and NGOs. In addition to the Advisory Board, the governance mechanism consists of the Coordination Board (representatives of institutions managing the coastal zone and the sea) and the Partnership Board (cities and municipalities).

County committee for coastal and marine management of the Šibenik-Knin County is established by the adoption of the Coastal Plan. This plan was developed between 2014 and 2015 and adopted in the County Assembly in 2016. The Plan was initiated by the County Department for Environment and municipal affairs. County committee for coastal and marine management is led by the County Prefect personally and with the Head of the Department for Environmental Protection and Municipal Affairs acting as Secretary. The Committee consists of the representatives of 11 organisations with major stakes in the coastal and marine issues. This body meets as need occurs, but not less than once a year, to coordinate the implementation of the Coastal Plan.

(https://adriadapt.eu/case-studies/coastal-plan-for-the-sibenik-knin-county-a-path-towards-resilience-and-sustainability/)

However, these advisory boards are limited in their legislative and executive powers. Also, they meet far too rarely to be able to participate in decision making or to be able to contribute in responding to policy concerns. Therefore, the frequency of the meetings, membership (represented institutions and power of the representatives) and placement of the Advisory body all are important issues for its efficiency and effectiveness. If Advisory body is placed into "bridging organisation" – organisation that explicitly focuses on mediation work between different disciplines, levels, or scales (Cash et al. 2006; Sauer et al. 2021), with the representatives from the top policy-making levels, the advisory body may perform at its best. Bridging organisations are essential for a network's governance capacities as they improve problem identification and dissemination of knowledge about local context, science, and regulatory communities; identify feasible and acceptable solutions and promote institutional mechanisms to best implement and monitor responses (Vignola et al. 2013; Sauer et al. 2021).

In 2021, Sauer et al. conducted an overall analysis of integrating climate change adaptation in the coastal governance of the Barcelona metropolitan area. This analysis found that the metropolitan administration acts as the most important bridging organisation, because of its role as a mediator between different city councils, consultants from science and technology, stakeholders, educational institutions and other actors from civil society, such as neighbourhood associations and environmental organisations. Authors identified that the centrality of the municipalities primarily lies in their task of the annual elaboration of the Beach Plans, (including all authorizations for occupations and activities carried out on the beach) as well as thanks to the Comprehensive Coastal Management Plan, which facilitates vertical and horizontal communication within the administration. The same analysis found that the actors responsible for climate change adaptation policies are in very peripheral positions in the network, which are caused by the lack of integration in coastal management. This situation confirmed the debate about the necessity and effectiveness of creating new offices that should be responsible for adaptation and mitigation of climate change, and confirmed that the formation of overarching institutions does not necessarily ensure robust adaptation (Preston et al. 2011; Sauer et al. 2021)

In the Barcelona case, scientific institutions and consultancies are mostly located in the outer periphery of the governance network, except one academic institution, which plays a role as a reference institute in investigations of coastal risks at the Catalan level. Although communication between the municipality and the academic institution is occasional and effective monitoring is likely missing, the fact that the local administration asks for expert judgement is to be interpreted as an indicator of trust. In this case, local expertise gained from coastal protection actions is not communicated to the higher administrative levels responsible for vulnerability assessments for national adaptation planning. This lack of vertical coordination limits the uptake of local scientific management experiences, effective adaptive management and learning opportunities.

Based on the all presented above, having Advisory Board with the top-level policymakers from all sectors, from all sciences, and at supra local/metropolitan area, nested in the bridging organisation could ensure proper positioning of the science-policy interface. It could be expected that the supra-municipal level, with responsibilities for maritime domain, beaches and/or spatial planning, are the right candidates to offer the nest for such an advisory body. Advisory bodies should have clearly and precisely defined responsibilities, tasks and ways of operating, inclusive and transparent membership with all sciences and all types of knowledge represented. Such a body should have a flexible way of operating, but with a permanent schedule and frequent meetings, in order to enable timely involvement of the scientists and experts in policy concerns at hand. The body could play the role of acting as the entry point into all institutions, organisations and groups acting in the relevant coastal zone. Information and Communication technology (ICT) provides the opportunity to make all contributions from all members permanently available on-line, for all interested citizens. In this manner, all involved scientists will share their work for the common good. Among the first tasks of such bodies should be the development of a coastal strategy and plan (in case these are not yet developed), so that decisions related to resilience and sustainability do not have to be taken without systemic approach, agreed long-term goals and the direction of actions. Finally, these bodies must be integrated vertically and horizontally in order to maximise their efficiency, transfer of knowledge and potential for accelerating climate action. Vertical integration would mean that such Advisory body exist at the national, sub-national and local level, and that they are established as a network. Not many advisory bodies at the national level are recognized as the leading bodies for the systemic transition of our societies. In France, for example, there is the « Haut Conseil du Climat » - could that be a body that secures a network of Advisory bodies?

According to historian Y.N. Harrari, the main reason why humans run the world lies in our ability to cooperate in large numbers; in our ability to create and sustain grand collaborative myths. This ability actually is the prerequisite for the SDG 17 – Partnership for results. However, in the early 21st century, humans have more power than knowledge, and more knowledge than the ability to cooperate. Therefore, we need science to help create a favourable environment for cooperation. We must focus more on the SDG 17 since in it lies our strength and weakness. We need a partnership for a new paradigm that would enable systemic transformation of our society towards sustainability.

New networks of science-policy interfaces, as the centres of the governance networks could be a way towards more science in policy making. Expanding science communication towards communities would be a step towards tomorrow's climate literate and aware citizens – the key to success for the systemic transformation.

4.8 Knowledge gaps (or "final remarks", "limits of assessment")

Addressing the adaptation challenges raised in the previous sections will require an integrated and systemic approach consistently applied across scales, from municipalities to governments (IPCC 2022 (SPM)). This can build upon existing integrated coastal management approaches, with more attention to system transitions compliant with sustainable development goals and climate and biodiversity targets.

It is worth noting that knowledge availability and accessibility at different sub-regions of the Mediterranean could enable better understanding the coastal risks facing the region, enable better cooperation and potentials for management of such risks.

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5 Sustainable Development Pathways

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5.0 Executive Summary and/or key messages

The attainment of climate resilient sustainable development pathways in the coastal areas of the Mediterranean remains a serious challenge. The pursuit of such pathways requires the proper identification of vulnerabilities related to human activities as well as climate change impacts, the assessment of opportunities to reduce risks to the affected communities, and the adoption of actions that are consistent with the Sustainable Development Goals (SDGs). The SDGs aim to shape most of the world's major priorities for livelihoods. Indeed, transformative actions are increasingly urgent across all sectors, systems, and scales to avoid exacerbating climate change risks and meet the SDG's goals (*high confidence*). In climate-resilient pathways, transformative actions concern leveraging change in key pillars of development that drive societal choices. Climate actions toward sustainability, such as social cohesion and equity, individual and agency, and knowledge developments, have been identified as crucial steps to transform practices and governance systems for increased resilience (*high confidence*). Mediterranean countries' efforts to adopt effective mitigation and adaptation measures are still insufficient to promote desirable and liveable futures, and to increase wellbeing for all Mediterranean coastal residents (*medium confidence*). Greenhouse gas emissions (GHG) in North Mediterranean countries (NMCs) have been systematically decreasing since 2005, whereas in south-eastern Mediterranean countries (SEMCs) they have been increasing continuously since the 1960s (*high confidence*). Economic and population growth, especially in SEMCs, combined with increased demand for the electrification of fleets, are the main factors for the observed rises in net emissions in the Mediterranean region, which has not yet managed to comprehensively decouple economic development from rising GHG emissions (*high confidence*). The most vulnerable actors of society, such as elderly, migrants, women, children and low-income earners, who are often more at risk, are not necessarily at the centre of policy measures that aim for an efficient and just transition to a changed environment and climate (*medium confidence*). Despite some progress in promoting a sustainable energy transition that moves away from fossil fuels towards renewable and clean energy sources, including solar energy, as well as efforts to support conservation and restoration of blue carbon pools such as coastal ecosystems, sustainable development pathways are not occurring at a sufficiently fast pace, thus risking of losing effectiveness against climate change impacts (*high confidence*). Marine renewable energy sources including offshore wind, wave, tidal current and thermal gradient energies are still in the early stages of development in the Mediterranean Sea, with only wind energy currently representing a feasible viable option (*medium confidence*). Importantly, further research is needed to establish the net impact of renewable energy sources on the unique Mediterranean biodiversity of coastal ecosystems (*medium confidence*).

Crucial socioeconomic sectors such as tourism, construction and real estate seem to be still largely based on linear and extractive models of development, insufficiently embracing circularity and sustainable development practices (*medium confidence*). A mix of economic instruments, command and control and behavioural nudges can be employed more vigorously by local, national and regional authorities, to promote effective climate resilient sustainable development pathways in the Mediterranean Basin, thus addressing environmental and climate change risks.

Key Messages

- GHG emissions in North Mediterranean countries have been systematically decreasing since 2005, while in South Eastern Mediterranean countries (SEMCs), they have been increasing continuously since the 1960s. Economic and population growth in SEMCs, coupled with increased demand for the electrification of fleets, are the main factors for the observed increases in net GHG emissions in the Mediterranean region (*high confidence*) (Section 5.2.1).
- Climate change, in combination with other global change drivers (urbanisation, rural exodus, population growth), represents a threat for vital ecosystems services located in Mediterranean marine and coastal ecosystems (*high confidence*) (Section 5.4.5)
- Circular and more sustainable models of development, especially in SEMCs, need to increase considerably and foster decoupling of energy consumption from economic growth, in order to reach carbon neutrality by 2050 (*high confidence*) (Section 5.2.2).
- Mediterranean countries have the potential to mitigate and adapt to climate change and contribute to the achievement of other SDGs through the proper conservation and restoration of blue carbon ecosystems, such as the coastal wetlands that include seagrass meadows and salt marshes, as well as coastal terrestrial ecosystems including coastal dunes. The carbon sequestration capacity of coastal wetlands is about 10 times that of terrestrial ecosystems but not sufficiently managed and protected (*medium confidence*) (Section 5.2.2).
- The promotion of an efficient and just transition to a changed environment and climate would require a careful analysis of distributional effects of policies in order to prioritise adaptation as well as other development programs, to avoid the risk of negatively impacting low-income earners and the most vulnerable (*medium confidence*) (Section 5.2.3).
- Coastal tourism is likely to act as a strong economic driver also in the near future, and as such it ought to play a more active role in contributing to foster sustainable development pathways, especially by shifting from generally wasteful and overconsumption practices to more circular and sustainable ones (*medium confidence*) (Section 5.3.1).
- Existing social inequalities across the Mediterranean Basin can act as a further barrier to climate change adaptation and sustainable development pathways (*high confidence*) (Section 5.4.1)

5.1 Introduction

5.1.1 Definitions and context

The concept of sustainable development has spread significantly since the early 1980s to become a core element of many policy documents adopted by governments, international agencies and business organisations (Mebratu, 1998). Consolidated in 1987 by the much-acclaimed Brundtland report, the term stressed that humanity has the ability to make development sustainable through efforts to ensure that it meets the needs of the present without compromising the ability of future generations (World Commission on the Environment and Development 1987). It also emphasised the need to impose limits to economic growth, especially in its excessive extractive and wasteful features, which are necessitated by the present state of technology and social organisation with regards to environmental resources, and by the limited ability of the biosphere to absorb the effects of current human activities. The report also brought to the forefront the three pillars of sustainable development, that is, the economic, social and environmental factors while pointing out that "what is needed now is a new era of economic growth - growth that is forceful and at the same time socially and environmentally sustainable" (World Commission on the Environment and Development 1987:7).

The three pillars of sustainable development gained a dominant position within the literature, and consequently in key policy documents. The concept is often represented in Venn diagrams or nested concentric circles of the three main pillars, and while the quest to operationalise it has raised some uncertainties and lack of clarity (Purvis et al. 2019), the adoption of the SDGs aims and targets contributes to improving the monitoring and evaluation of concrete actions to integrate the three dimensions of sustainable development within the UN system (UN, 2012) and across various countries. In recent years, since the evolution of the concept of sustainable development, other approaches have emerged, such as wellbeing (Layard and Layard, 2011), doughnut economics (Ross 2019), de-growth (Demaria et al. 2013), and *buen vivir* (Tolentino 2015), all with the aim of minimising the overall carbon footprint, fostering a harmonious relationship between nature and human activities, and a fairer distribution of resources and access to services among human populations. Nevertheless, sustainable development is still firmly enshrined as a global concept among the key trajectories for many international organisations, nation states and their official deliberations.

However, the shift to sustainable development is not achieved overnight and particular trajectories need to be actively pursued. These are referred to as Sustainable Development Pathways. The definition adopted for these pathways in this chapter follows that utilised in the IPCC AR6 (2022) and refers to trajectories that involve "transitions aligned with a shared aspiration in the Sustainable Development Goals (SDGs)" (IPCC 2022: Annex I: Glossary: 40), with efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation to and resilience in a changing climate". These pathways involve the ethics, equity, and feasibility aspects of societal transformations in society, based on an array of social, economic, cultural, technological, institutional, and biophysical features that characterise the interactions between human and natural systems, with the aim of drastically reducing emissions to limit global warming, while achieving desirable and liveable future and well-being for all (IPCC 2022). The pursuit of climate-resilient pathways involves identifying vulnerabilities to climate change impacts, assessing opportunities for reducing risks, and taking actions that are consistent with the sustainable development goals. The clean energy share in industry (SDG 7) and air pollution concentration in cities (SDG 11) show positive trends and synergies with climate policies. Most developmental indicators (SDG poverty, SDG energy access) have trade-offs with climate policies (SDG 13), largely driven by higher energy and food prices (Soergel et al. 2021). Country size and sovereignty can also play a role in the capacity of countries to attain SDGs (Moncada and Randal 2022).

In this chapter the specific context targeted is the Mediterranean Basin, especially coastal areas and their communities, with the aim of identifying and assessing sustainable development pathways, including barriers to achieve them.

5.1.2 Layout of the chapter

Following this introduction, the chapter will first discuss the Regional contributions and responses to climate stress and uncertainty in the Mediterranean Basin, looking at GHG emissions and the current status of NDCs' plans for the countries belonging to the Mediterranean area. Section three discusses the sustainable pathways in the context of the SDGs, while section four focuses on the specific topics of social and climate justice, including climate finance, with section five concluding.

5.2 Climate change related stress in the Mediterranean

GHG emissions are considered the overarching driver for climate induced changes that contribute to local coastal risks and hazards, including sea level rise, flooding, ocean acidification, among others (*high confidence*) (see *Chapter 2*). This section highlights the regional contributions to global GHG emissions, identifies the mitigation and adaptation measures that individual governments in the

Mediterranean basin communicated in their initial and subsequent Nationally Determined Contributions (NDCs), in addition to other publicly documented measures, to combat climate change; evaluates the benefits and co-benefits of such measures, and, finally, determines the extent of the support that these measures provide towards the attainment of the SDGs, highlighting any dissonance toward the desirable attainment of sustainable development pathways.

5.2.1 GHG Emissions in the Mediterranean: a short summary

Over the past 50 years, the distribution of energy consumption within the Mediterranean region has changed dramatically. **Table 5.1** summarises the shift in energy consumption across the Mediterranean Region. During the early 1970s, North Africa consumed only 4% of the total energy generated, whereas the European countries consumed 81%. In 2016, North Africa's share increased to 19% while that of the European Union decreased to 59%. During the same period, per capita consumption in North Africa and the Middle East also increased relative to Europe, although the gap remains very wide. Türkiye also registered a significant increase in the consumption of fossil fuels and CO_2 emissions, starting in the 1990s (UNEP/MAP and Plan Bleu 2020; Bartoletto 2022) (*high confidence)*.

Table 5.1 | Shifts in energy consumption in the Mediterranean between the 1970s and 2016. *Source: Bartoletto, 2022*

Year	Location	Consumption of energy
1970s	North Africa	4%
	Europe	81%
2016	North Africa	19%
	EU	59%

By the year 2000, 72% of the GHG emissions consisted of CO_2 connected with energy use (77% in the Northern Mediterranean Countries (NMCs) and 64% in the Southern and Eastern Mediterranean Countries (SEMCs). Historically, the growth of CO_2 emissions has been far more rapid in the SEMCs than in the NMCs. Whereas the NMCs reported an increase of 18% (mainly due to the transport sector) between 1990 and 2004, the emissions of the SEMCs increased by 58% over the same period (mainly due to electricity and heating). This growth rate is twenty points higher than the world average rate (EIB 2008), highlighting potential negative impacts for environmental and climate risks (*medium confidence*).

Despite this, the current share of carbon emissions of the Mediterranean countries amounts to no more than 6 percent of global emissions (FAO and Plan Bleu 2018), with NMCs contributing the larger proportion. The 2020 report on the State of the Environment and Development in the Mediterranean notes that emissions in NMCs reached their peak in 2005 but have since then decreased. On the other hand, in SEMCs, CO_2 emissions have been increasing continuously since the 1960s. In 2014, the two regions were responsible for 1Gt of CO_2 emissions (UNEP/MAP and Plan Bleu 2020) *(high confidence)*. This clashes with the requirements of the Paris Agreement which necessitates that net CO_2 emissions decline significantly. However, according to current and future GHG emission projections, trends do not show a promising path in their reduction (Ali et al. 2022). This is likely to be the result of the intermediate economic development of SEMCs, together with the final stages of democratic transition, which brought changes in the working population, shifting consumption modes and resulting in an increase in energy, infrastructure and housing demand (European Investment Bank 2008). Energy demand, especially, is expected to continue its upward trend in the next few decades (Plan Bleu and European Investment Bank 2008) given the expected growth in the population and economies of the Southern Mediterranean Region (Ben Jannet Allal et al. 2016) but also given the electrification of fleets, which is not being accompanied by the same level of supply of renewable energy production (Milovanoff et al. 2020) *(high confidence)*.

The most recent inventory of net GHG emissions (see **Table 5.2**) indicates that NMCs emitted a total of 1.2 million kt CO_2 equivalent, representing 8% of the total reported by Annex 1[6] countries in 2019. While Annex 1 countries report a decline of 18.94% in net emissions between the base year and the latest inventory, the Mediterranean Basin countries in Annex 1 report an increase of 10.26% during the same period, attributed mainly to Türkiye's emissions increase of 158%.

Table 5.2 shows the CO_2 equivalent emissions according to the latest year availability inventory for Annex 1 and Non-Annex 1 countries. The percentage change of emissions from the indicated base year for every country is in columns 4 and 5. As can be noted, the three Balkan countries - Bosnia and Herzegovina, Croatia and Montenegro, all registered a substantial decrease in emissions. On the other hand, Egypt and Morocco, registered a substantial increase in emissions. Increases were also registered by Tunisia, Syria, Lebanon, Israel and Cyprus while no figures are shown for Libya. Between 1990 and 2019, GHG emissions from these countries registered a net increase of 391.49% (UNFCCC 2023).

[6] Annex 1 countries refer to industrialised countries and economies in transition. Non-Annex 1 parties are mostly developing countries. In the Mediterranean, 13 countries are Non-Annex 1 countries, while the remaining 8 countries are Annex 1.

Table 5.2 | Changes in GHG Emissions in the Mediterranean. *Source: GHG data from UNFCCC https://www.unfcc.int*

Country	**Party/Region**	**Base year/Latest Year: net GHG Inventory (kt CO_2 equivalent)**	**Change in % (base year to latest inventory year)**	**Yearly average change in %**
Albania	Non Annex1	1990/2009: 9,037	15.36	0.76
Algeria	Non Annex1	1994/2000: 103,143	2.79	0.46
Bosnia and Herzegovina	Non Annex1	1990/2014: 19,342	–27.34	–1.32
Croatia	Non Annex1	1990/2019: 18,048	–27.63	–1.11
Cyprus	Non Annex1	1990/2019: 8,457	58.02	1.59
Egypt	Non Annex1	1990/2005: 241,632	126.16	5.59
France	Annex 1	1990/2019: 412,579	–21.49	–0.83
Greece	Annex 1	1990/2019: 82,150	–18.81	–0.72
Israel	Non Annex1	1996/2019: 79,045	37.99	1.41
Italy	Annex 1	1990/2019: 376,719	–26.88	–1.07
Lebanon	Non Annex1	1994/2013: 22,766	43.10	1.90
Libya	Non Annex1	nil	nil	nil
Malta	Annex 1	1990/2019: 2,175	–16.43	–0.62
Monaco	Annex 1	1990/2019: 83	–19.59	–0.75

Montenegro	Non Annex1	1990/2011: 1,697	–58.33	–4.08
Morocco	Non Annex1	1994/2012: 100,545	152.10	5.27
Slovenia	Annex 1	1986/2019: 16,964	8.66	0.25
Spain	Annex 1	1990/2019: 276,952	9.03	0.30
Syria	Non Annex1	1994/2005: 79,216	50.07	3.76
Tunisia	Non Annex1	1994/2000: 32,096	37.35	5.43
Türkiye	Annex 1	1990/2019: 422,085	157.69	3.32
Annex 1	Total	1990/2019: 14,555,211	–18.94	–0.72
Non Annex 1	Total	na	na	na

In the Annex 1 countries, listed in **Table 5.2**, emissions are much higher than those of non-annexes 1 countries. The increased efficiency is mostly in EUMS, which resulted in a much less drastic increase in emissions. In fact, between 1990 and 2019 the net increase in emissions was 72.18%. (*high confidence*). Annex 1 countries are home to 271,553,157 people, 81.5 million more than non-annex 1 countries, hosting 189,975,880 people[7] *(high confidence).*

5.2.2 Mitigation and adaptation efforts and the NDCs in the Mediterranean Basin

Mediterranean countries have the potential to mitigate climate change through energy transition and interventions that include a reduction in the use of fossil fuels and an increased adoption of renewable energy sources (*high confidence*). The implications of Russia's war in Ukraine brought up the issue of energy security into the forefront. Europe's strong dependence on energy supply from Russia is now forcing it to find alternative sources to maintain the security of supply in the region. Diversifying the energy sourcing in addition to relying on renewable sources would be the key to energy security in the near future. This is especially relevant for all coastal areas, given their strategic location in terms of production and transportation of such renewable sources (*medium confidence*). According to the Observatoire Méditerranéen de l'Energie (OME), in 2030, even if all NDCs are reached, fossil fuels will still account for 71% of the energy mix in the region due to the inertia of transport and industry demand that cannot be hastily displaced. In a net-zero carbon future, renewables will need to step-up to reach 57% of the total mix by 2050 (OME 2022). The transition to resilient energy efficient pathways requires a significant transformation of energy

[7] https://www.worldometers.info/world-population/ as on 17/05/2022 -

policies and economic models in Mediterranean countries (Feleki and Moussiopoulos 2021). While the NMCs have the resources and facilities to make the leap towards the transition, some of the SEMCs need support, knowledge transfer, funding and capacity building programs (*high confidence*).

According to OME, to reach carbon neutrality by 2050, energy demand in the NMCs will need to be reduced by a further 41%, whereas the increase in demand in the SEMCs should be capped at under 2% by 2050 from its current levels. Moreover, the fuel mix will need to be 57% renewables, 17% nuclear and 26% fossil (23% for gas alone – the least carbon intensive fossil fuel). At present, fossil fuels account for 76% of the energy mix (65% in the North and 92% in the South) and it will need to go down to less than 22%. Renewables, although fast increasing, stand at only 12% of the total Mediterranean energy demand and while that share reaches 15% in the North, it is barely attaining 8% of total energy demand in the South (OME 2022).

In the decades ahead, most capacity additions will stem from renewables and nearly all from solar and wind technologies. OME (2022) argues that the region needs to generate 600 GW of net additional capacity from solar energy and 500 GW from wind energy both onshore and offshore technologies, by 2050.

Current solar capacity stands at 85 GW in the total Mediterranean region (OME 2022). By the end of 2018, around 2.9 GW of solar PV were operating in the Middle East and North Africa area, with 12 GW of solar projects under construction or awarded. The SEMCs have huge solar irradiation levels making them ideal for large-scale development of solar PV power. For example, while Algeria currently hosts only 500 MW of PV power, its national plan for the development of renewable energy renewable energy indicates that around 60% of new renewable energy power (around 13575 MW) would originate from solar PV and 5010 MW from wind power (Ciriminna et al.2019).

Marine renewable energy sources, while feasible for coastal areas in general, are still in the early stages of development in the Mediterranean Sea. The blue energy sources include the use of offshore wind, wave, tidal current and thermal gradient energies. The potential for using these sources of energy varies dramatically in the Med Basin, with wind energy being a feasible alternative and wave energy still being a limited option (*low to medium confidence*). A large number of offshore wind projects are at a concept/early planning stage in the north of the Mediterranean - notably in France, Greece, Italy and Portugal. According to Soukissian et al. (2017), the Gulf of Lion and the Aegean Sea are the most favourable areas for offshore wind energy projects in terms of potential (with 1,050 and 890 W m^{-2}, respectively) at 80 metres above the sea level. Additional candidate areas include the Adriatic Sea and the Gulf of Gabes, when bottom depth suitability is considered. The first offshore wind farm was inaugurated, in April 2022, off the coast of Italy with a total capacity of 30 megawatts (MW) and an estimated output of 58,000 megawatt-hours (MWh) per year, enough to power 21,000 homes. By 2028, two offshore wind parks are expected to be operational, off the coast of Sicily, with a total capacity of 750 MW, estimated to generate over 2,000 GWh of electricity annually, equal to the average annual power demand of about 750,000 homes. Three pilot projects of floating offshore farms have been approved in the Gulf of Lion, France, and are due to be built before 2023 (Plan Bleu, 2022). The European Wind Energy Association (EWEA) projects that, by 2030, 150 GW could be produced using wind power in Europe’s coastal waters; energy sufficient to service the electricity demands of 145 million households. By 2050, EWEA predicts that offshore wind could reach 460 GW, producing 1,813 TWh of electricity, equivalent to 50% of the European electricity supply (Piante and Ody, 2015). The Mediterranean Sea has a very low wave energy resource with the highest average wave power in the region being around 6 kW m^{-1}. Wave energy is more expensive than offshore wind energy and its technological development is far behind wind turbine technological developments. Hence, it is expected that the development of wave energy will be slow and limited in the future. Tidal resources are currently limited to the Straits of Messina, Bosphorous and Gibraltar. The development of electricity based on tides and currents will remain limited in the future (Piante and Ody 2015). The information is summarised in **Table 5.3 below**.

Table 5.3 | Current and future energy policies in the Mediterranean.

Current energy situation	**Projected policies**
76% originates from fossil fuel, 12 % from renewables	A significant energy transformation is required to reach carbon neutrality by 2050. Energy fuel mix must be 57% renewables, 17% nuclear and 26% fossil (out of which 23% is gas).
Wind energy is gaining popularity for example Italy inaugurated a farm with 30MW that can power 21,00 homes	More wind energy is planned for example by 2028 a 750 MW wind farm in Sicily with the ability to power 750,000 homes together with the Gulf of Lion, France. By 2050, wind energy could reach 460GW.
Data not available	Tidal energy potential is limited due to limitations in wave power. Still expensive and technological developments are limited.

Almost all countries (except Libya) in the Med Basin have committed through their INDCs or updated NDCs to reducing energy consumption and employing renewable energy sources to reduce GHG emissions, by 2030.

In North Africa, Morocco's renewable energy target of 52% stands out as the most ambitious plan in the region. Morocco, in fact, committed to reducing its GHG emissions by 42%, with an unconditional reduction target of 17% by 2030. Algeria committed to reducing energy consumption by 9% and deriving 27% of all electricity production from renewable sources. Tunisia declared its intentions to reduce its carbon intensity by 41 per cent compared to 2010, and adopt renewable energy sources to power desalination plants in addition to using more efficient desalination techniques. Finally, Egypt committed to reducing its energy intensities and promoting low-carbon technologies in addition to decreasing all sources of emissions, however, without explicitly specifying the targets (OME 2022).

The European Union, in its initial and binding NDC, has targeted an economy-wide net reduction of at least 55% of GHG emissions from base year values, without contributions from international credits. Considering the implications of Covid-19 on its economy, a decision was made to deliver at least the reductions pledged in the EU's initial NDC. The efficiency of the EU's final and primary energy consumption will be improved by at least 32.5% by 2030 as compared to an historic baseline. A new target for increasing renewable energy in final energy consumption has been set to reach at least 32% by 2030 (Kulovesi and Oberthür 2020).

Elsewhere in Europe, the Principality of Monaco plans to achieve carbon neutrality by 2050. The pledge is to reduce its GHG emissions by 30% by 2020 and 80% by 2050, compared with the base year. Albania intends to reduce CO_2 by only 11.5% by 2030, since it generates all its electricity using renewable sources (hydropower) and there is limited possibility for further reduction. It plans to increase the share of renewable energy use (in gross final energy consumption) to 42% by 2030[8]. Bosnia and Herzegovina set an unconditional GHG emissions reduction target for 2030 of 33.2% and a conditional target (with more intensive international assistance for the decarbonisation of mining areas) of 36.8% relative to 1990. GHG emissions reduction target for 2050 is 61.7% (unconditional) and 65.6% (conditional) compared to 1990. Bosnia and Herzegovina plans to install mini hydro power plants, wind farms, and photovoltaic modules with a total energy generation capacity of 120 MW, 175 MW and 4 MW respectively, by 2030. Finally, Montenegro committed to an economy-wide GHG emission reduction target of 35% by 2030 compared to base year (1990) emissions, excluding Land Use, Land-Use Change and Forestry (LULUCF). The reduction is to be achieved by general increase of energy efficiency, improvement of industrial technologies, increase of the share of renewables and modernization in the power sector.

In the Middle East, Türkiye has a mitigation plan to reduce GHG emissions by 21% by 2030. The plan includes the use of solar power to generate 10 GW electricity, wind power to generate 16 GW, nuclear power and full tapping to hydroelectric power. Moreover, the plan intends to reduce losses from electricity transmission and distribution to 15% by 2030. Lebanon intends to reduce emissions, and increase renewable energy use, by 15% each and improve energy-efficiency levels by 3%, conditional on financing. Syria pledged to reduce dependence on fossil fuels and intends to increase renewable energy use to 10% by 2030. Israel committed to an economy-wide unconditional target of reducing its emissions by 26% below relative to 2005, through energy efficiency (17% reduction in electricity consumption) and use of renewable energy (17% of the electricity generated) in 2030. Furthermore, it committed to a 30% reduction of greenhouse gas emissions from electricity generation by 2030 and 85% by 2050 compared to emissions measured in 2015. The information is summarised in **Table 5.4** below.

Mediterranean countries have the potential to mitigate climate change and contribute to the achievement of other SDGs through the proper conservation and restoration of blue carbon ecosystems such as the coastal wetlands (e.g, coastal lagoons, seagrass meadows and salt marshes (see for instance Eid et al. 2017), but also of coastal terrestrial ecosystems (Leal Filho et al. 2020), including coastal dunes (Drius et al. 2019b). These coastal ecosystems are important and contribute to the well-being of people and nature by providing good-quality water, acting as a barrier to negative effects of extreme climatic events, contributing to food production, and by preserving biodiversity (Spalding et al. 2014; Aurelle et al. 2022). The carbon sequestration capacity of coastal wetlands is about 10 times that of terrestrial ecosystems (McLeod et al. 2011). *Posidonia oceanica*, endemic to the Mediterranean Sea and sometimes referred to as "the lungs of the Mediterranean", is the most widespread seagrass species in these waters (*high confidence*). It has a significant role as a carbon sink, absorbing carbon dioxide, storing carbon at an average rate of 83 g C m^{-2} per year, and helping to alleviate the effects of climate change. It covers between 25,000 and 50,000 km^2 of the coastal areas, corresponding to 25% of the sea bottom at the depth between 0 and 40 m. The Mediterranean *Posidonia* population produces 14 to 20 litres of oxygen per square metre every day (Mediterranean Advanced Research Institute (IMEDEA and the BBVA Foundation 2017). The *Posidonia* population, listed on the IUCN Red List of Threatened species, has been declining at the rate of approximately 10% over the last 100 years, with recent estimates of over 30% in the past 50 years, in many parts of the Mediterranean, due to pollution, coastal development, fishing activities, the mooring of ships (Telesca et al. 2015; Boudouresque et al. 2009)[9], and climate change (Chefaoui et al. 2018).

[8] Albania intends to sell carbon credits during the period until 2030 to contribute to cost-effective implementation of the low emission development pathway and its sustainable development.

[9] https://medwet.org/2017/10/mediterranean-posidonia/

Proper valuation and pricing of Mediterranean blue carbon ecosystems that primarily include seagrasses and salt marshes could allow conservation and restoration initiatives that carry the

Climate change adaptation has been identified as an essential policy response (Eriksen et al. 2011). However, although increasing in importance, it has received less attention when compared to mitigation in terms of legislative and funding interventions (Sietsma et al. 2021). In the Mediterranean region, especially in its coastal areas, climate change adaptation can play a central role to support the resilience of ecosystems to climate risks (Aurelle et al. 2022). Furthermore, the vast traditional ecological knowledge heritage present in the Mediterranean can be used for adaptation, promoting for instance more agroforestry practices that would increase livelihoods while adapting to climate change (Aguilera et al. 2020) (*high confidence*).

Table 5.4 | Commitments of Mediterranean countries to reduce GHG emissions. Source: UNFCCC 2023

Country	**Target**	**Additional comments**
Morocco	↓ 52%	17% to be unconditionally reduced by 2030
Algeria	↓ energy consumption by 9%, while 27% of energy is derived from renewable sources.	no additional information available
Tunisia	↓ 41% compared to 2010	Modernise desalination plants with renewable energy
Egypt	No target specified	
EU	↑ renewable energy by at least 32% by 2030.	no additional information available
Monaco	Carbon neutrality by 2050	Reduce GHG emissions by 30% by 2020 and 80% by 2050, compared to base year
Albania	↓ CO_2 by 11.5% by 2030	All electricity is generated using renewable sources.
Bosnia and Herzegovina	no additional information available	Plans to install mini hydro power plants, wind farms, and photovoltaic modules with a total energy generation capacity of 120 MW, 175 MW and 4 MW respectively, by 2030.
Montenegro	↓ 35% of GHG emissions by 2030	no additional information available
Türkiye	↓ GHG by 21% by 2030	10 GW derived from solar power, 16GW from wind power, the remaining from nuclear and hydroelectric power. Reduce losses from electricity transmission and distribution to 15% by 2030.
Lebanon	↓ emissions and ↑ use of renewable energy by 15%	Improve energy-efficiency levels by 3%.
Syria	↓ dependence on fossil fuels and ↑ renewable energy use to 10% by 2030	no additional information available

Israel	↓ emissions by 26% below 2005 figures	To be achieved by improving energy efficiency (17% reduction in electricity consumption) and use of renewable energy (17% of the electricity generated) by 2030.

5.2.3 Net benefits and co-benefits of mitigation and adaptation

Mitigation of and adaptation to environmental pollution and climate change impacts, while not without cost or residual damage, may substantially reduce the adverse risks, and/or enhance co-benefits to possibly spill over to societal wellbeing (Smit and Pilifosova, 2001). Taking into consideration the case of the offshore wind farms, their construction may introduce or add pollutants (synthetic and non-synthetic compounds) to the sea, in addition to the disruption it may cause during the construction phase. The environmental effects of offshore wind farms in the Mediterranean are poorly studied (Bray et al. 2016; Lloret et al. 2022) (*medium confidence*). Since the Mediterranean is a semi-closed sea with particular characteristics including minimal tidal ranges, high levels of biodiversity and endemism (Coll et al. 2010), and a high potential of non-indigenous species invasion (e.g., Kourantidou et al. 2021), the effects of existing offshore wind farms may not be directly applicable to the Mediterranean, highlighting the urgent need for site-specific analyses (Bray et al. 2016; Lloret et al. 2022) (*medium confidence*). In detail, the Mediterranean Sea hosts endemic seabird species for which there is no impact assessment yet. It is also a major and crucial transit route for Saharan-Eurasian migration, as evidenced by both the Mediterranean-Black Sea flyway and the Adriatic flyway (Bray et al. 2016) (*high confidence*). Wind farms affect resident and migrating birds, through avoidance behaviours, habitat displacement, and collision mortality (e.g., Dierschke and Furness 2016). Considering marine mammals, both resident and visiting species, of which most are experiencing a decline in population trends, occur in the Mediterranean Sea. The principal negative impacts to marine mammals and fish populations caused by wind farms are noise and electro-magnetic fields. Although research has indicated that some species of seabirds strongly and consistently avoid offshore wind farms, thus minimising impacts and possible effects on the bird population, other species (mostly cormorant) tend to be more negatively impacted by such wind farms (Dierschke and Furness. 2016), calling for further investigation in the Mediterranean (Bray et al. 2016; Lloret et al. 2022) (*medium confidence*).

Some studies argue that offshore wind farms could be beneficial for benthic habitats and animals, because they offer an artificial reef that may provide space for the settlement, shelter and foraging (e.g., Mavraki et al. 2020). This apparent benefit should be carefully assessed in the case of the Mediterranean Sea, due to its high habitat heterogeneity. On the one side, long-term effects of ecosystem shifts are unknown; on the other side, the creation of new and artificial substrates favours colonisation by opportunistic species and the arrival of non-indigenous species that can alter the local biodiversity balance (Lloret et al. 2022) (*medium confidence*).

While mitigation efforts are important, enhancement of adaptive capacity is a necessary condition for reducing vulnerability, especially for the most vulnerable regions and socioeconomic groups. Activities that usually improve adaptive capacity also promote sustainable development (*high confidence*). In coastal zones, improving adaptive capacity may require a wide array of measures including planting salt-tolerant varieties of vegetation, establishing agricultural practices that are more resistant to flood (Maggio et al. 2011), planting mangroves for flood protection, developing desalination techniques, establishing mechanisms for disaster response, and empowering communities to build resilience to extreme events (Iglesias et al. 2018), among others.

Pollution reduction (mainly water pollution from wastewater and urban runoff), improves human health (from waterborne diseases, food poisoning from chemical discharges and contaminated fish consumption) (Analitis et al. 2018), development of sustainable energy systems for both use in industrial production and consumption (renewable energy production and use) (Pisacane et al. 2018; Kougias et al. 2019), employing less-intensive industrial fishing practices (Giordano et al. 2019), although these must be appropriately regulated for environmental recovery programs in order to be effective and not damaging marine ecosystems (Enrichetti et al. 2019) (*high confidence*).

Mitigation and adaptation efforts will potentially affect the availability and prices of energy, food (fisheries, aquaculture) and other ecosystem-intensive services (tourism) *(medium to high confidence*). Sustainable development pathways will necessitate social mobilisation and necessary investments in capacity building to avoid exclusion and protection of interests and rights of people vulnerable to the impacts of climate change, and of future generations (UNEP 2019).

While it is relevant to understand the relative importance of different kinds of interventions (mitigation and adaptation) but also the potential positive and negative synergies between them. A proper assessment of outcomes would require that policy makers conduct a cost-benefit analysis complemented by an analysis of distributional effects in order to prioritise adaptation programs as well as other development programs to promote an efficient and just transition to a changed climate (Bellon and Massetti 2022) (*high confidence*).

Boyd et al (2022) argue that the alignment of adaptation and development goals is a more common aim than the alignment of adaptation and mitigation. Hence, they advocate creating incentives to meet multiple policy priorities, reduce costs, and increase resource efficiency and institute co-benefit approaches that cover adaptation, mitigation, and development goals.

5.3 Sustainable pathways and significant targets across SDGs

This section briefly introduces the SDGs and discusses current efforts to achieve their targets, including a focus on sustainability pathways in the Mediterranean Basin. It also highlights the impacts of sustainability measures on a range of different sectors, especially those most significantly impacting on climate change in the context of coastal communities. It will continue by discussing short-term (2021–2040), versus mid-term (2041–2060) and long-term (2061–2100) efforts to achieve sustainability pathways and how the trade-offs between different SDGs goals can potentially lead to favourable transition for new sustainable pathways. This section will also discuss how policies, data, technology and communication can act as catalysts for effective and long-lasting development pathways.

In 2015, 17 SDGs were adopted by all UN member states. Also known as Global Goals, the SDGs aim to provide a universal call to end poverty, protect the planet and ensure that by 2030 all people are on the path to enjoy peace and prosperity. Each SDG has a set of indicators, some of which are multipurpose and are used to monitor more than one SDG, and more than one of the three pillars of sustainable development.

For the first time since the adoption of the SDGs, the average score for the 2020 Global Sustainable Development Goals Index has fallen from the previous year, affecting all the three dimensions of sustainability. The coronavirus disease (COVID-19) pandemic, a growing population, and other crises have clearly been major setbacks for attaining sustainable development (Sustainable Development Report 2020). In 2021, the negative impacts brought by the COVID-19 pandemic, especially in the area of reduced connectivity and economic activities, continued to be a major factor contributing to high rates of poverty and unemployment, which prompted an overall decline in the performance of the sustainable development goals at the global level (Shulla et al. 2021). The economic and financial shocks associated with COVID-19 also impacted the funding for sustainability, making it more difficult and undermining the general approach toward achieving the 17 SDGs by the established 2030 deadlines, therefore slowing down the set trajectory of development (*medium to high confidence*). The overarching aim of "leave no one behind" is threatened by the current growing inequalities (Shulla et al. 2021). Lack of resources, especially in funding, ought to prompt a need for interdisciplinary thinking systems, allowing key policies, such as trade and technological innovation, to support the attainment of the sustainable development goals (Sustainable Development Report 2022). There is *robust evidence* that current development pathways are leading away from sustainable development (IPCC 2022) (*high confidence*).

Mediterranean countries do not seem to be on the right track to achieve most of the SDGs (Sustainable Development Report 2022). They appear to be performing well on some of the SDGs, such as eradicating poverty (Goal 1), promoting good health and well-being (Goal 3), and quality education (Goal 4). However, they score poorly and underperform quite alarmingly in areas such as: biodiversity protection, including life underwater (Goal 14) and life on land (Goal 15), and climate change (Goal 13); social integration, including gender equality (Goal 5) and reduced inequalities (Goal 10). The Mediterranean region is the second most vulnerable to climate change after the Arctic (MedECC 2020), apart from other vulnerabilities, broadly connected to political, economic, social and environmental imbalances, also exacerbated by differences across geographical regions, which can grow even bigger due to the negative impacts of climate change in the region. Current regional and cross-country partnerships can support the uptake of sustainable development initiatives in the Mediterranean, including measures supported by the European Union, the Union for the Mediterranean, the United Nations Environmental Programme Mediterranean Action Plan, among others, in the spirit of SDG 17 (Partnership for the goals), to foster sustainable pathways.

5.3.1 Determining the pathways to sustainability for major sectors

It is well known that climate change impacts bring down the ability of countries to achieve sustainable development (United Nations 2015), and that these impacts can take away improvements in living conditions and decades of progress on development pathways. For instance, dangerous levels of climate change are likely to limit efforts in reducing poverty, as its negative impacts are more severely felt by low-income and vulnerable people, especially because of their high dependence on natural resources, which are becoming scarcer and less accessible, and the limited capacity of low-income and vulnerable groups to properly cope with climate variability and extremes (Hallegatte and Rozenberg 2017) (*high confidence*).

The adoption of the Paris Agreement and the 2030 Agenda demonstrated a growing international consensus on the need to pursue climate change as a component of sustainable development. For example, increased levels of warming may narrow the choices and options for sustainable development. However, it is important to remember that the Paris Agreement is not static; it is designed to enhance the national efforts of countries over time, which means that current commitments only represent the basis of climate change ambition. The heavy lifting that carries more emissions still needs to be done by 2030 and 2050, and the agreement should provide the tools and innovative approaches to make it happen (NRDC 2021). Furthermore, as reported by the IPCC WGII Sixth Assessment Report (2022), recent studies assessing the links between development and climate risk shows that actions taken to achieve the goals of the Paris Agreement could undermine progress toward some of the SDGs. Effective sustainable development pathways in this regard are also those that consider the impact of any mitigation and adaptation measures on marginalised and vulnerable people (Hickel 2017). Although considerations of social difference and access to justice might be included in some of those measures, the assumption that economic growth increases opportunities for all, and distributes the newly created financial resources equally, might not be correct, coupled with climate change impacts affecting the most vulnerable sectors of society disproportionately more (Diffenbaugh and Burke 2019) (*medium confidence*).

To achieve the SDGs and to consolidate the shift to sustainable development pathways is still possible by the deadline of 2030, if a more ambitious climate policy, international climate finance, gradual redistribution of carbon pricing dividends, technological progress, less resource-intensive lifestyles, and improved access to modern energy are undertaken in the short-term (2021–2040), as also shown by **Figure 5.1** (Soergel et al. 2021) (*low confidence*).

In 2019, the Sustainable Development Solutions Network published a report which focused on the performance of 23 Mediterranean countries with regards to the SDGs. The report states that the average SDG index for the region reached 71.6 which corresponds to the 49th position in the world rank, and therefore, almost 72% away from the best possible outcomes across the 17 SDGs. The countries registering the most progress with most SDGs are NMCs. Good progress was also made by most Mediterranean countries in the provision of basic services and infrastructures, particularly under SDG 1 (no poverty), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy) and partially in SDG 8 (decent work and economic growth). However, the report points out that even the countries topping the list are far from achieving the highest score of 100 (Mediterranean Sustainable Development Solutions Network 2019).

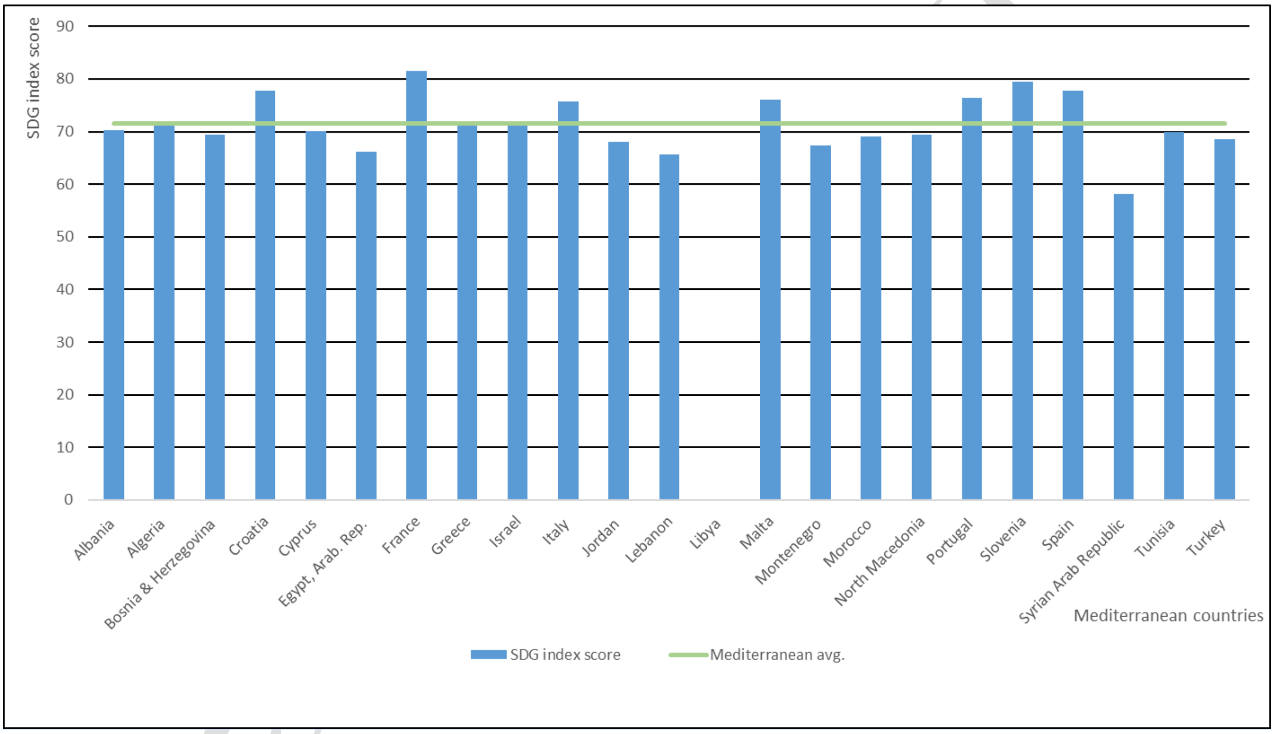

Figure 5.1 | Mediterranean SDG index score. Source: Sustainable Development Solutions Network (2019)

5.3.1.1 Pathways for sustainable energy and climate mitigation

Mediterranean countries have a very different mix of energy sources; while most countries are net energy importers others are net energy exporters. These differences complicate envisioning a common pathway for sustainable energy and climate mitigation in the Mediterranean, and even planning observations that can be applied to the region as a whole (*medium confidence*). It is undeniable that the Mediterranean region would benefit from sustainable energy and climate mitigation pathways, since energy and climate issues are at the forefront in the Mediterranean region. Fostering a sustainable and future-proof socio-economic development model based on sustainable low carbon energy and climate mitigation pathways is also an essential component of regional stability (Antonelli et al. 2021) (*medium confidence*).

The European Union *Green Deal* has been framed as a broad political vision that summarises the EU's energy, climate, economic and geopolitical ambitions goals of reaching climate neutrality by 2050, supporting measures to reduce the carbon footprint of hydrocarbon production and energy efficiency. Hydrogen can be a key enabler of Mediterranean decarbonization intentions, as there is unprecedented momentum for capital-intensive hydrogen projects, including across the Mediterranean (*low confidence*). Accordingly, when promoting green energy and climate mitigation pathways in the region, preference will likely go to low-carbon projects that will in fact contribute to reducing global warming and achieving socio-economic goals in the region, compared to other solutions, they also appear to be future-proof, consistent with net zero targets by mid-century (Antonelli et al. 2021) (*medium confidence*).

All Mediterranean governments must implement clear action plans to close the electricity access gap, backed by determined leadership, increased investments and targeted policies and regulations. Multi-stakeholder partnerships and scaling up for supporting investments in clean energy across all sectors of the industries introducing the transition to clean energy is essential for reaching the net zero goal by 2050 (UN Sustainable Development Report 2019).

SEMCs have natural resources that provide opportunities for low-carbon energy production. However, the share of renewable energies over the total energy consumption remains low because of widespread fossil fuel subsidies, regulatory restrictions, and limited electrical connectivity (*high confidence*). Clean energy still accounts for a relatively small share of the North-South trade. In this context, SEMCs may use green and blue hydrogen as crucial elements of their decarbonization strategy, such as the initiatives of countries like Egypt, Morocco and Tunisia, which have recently signed bilateral projects with Germany on green hydrogen projects (**Figure 5.2**) (Moreno-Dodson et al. 2021).

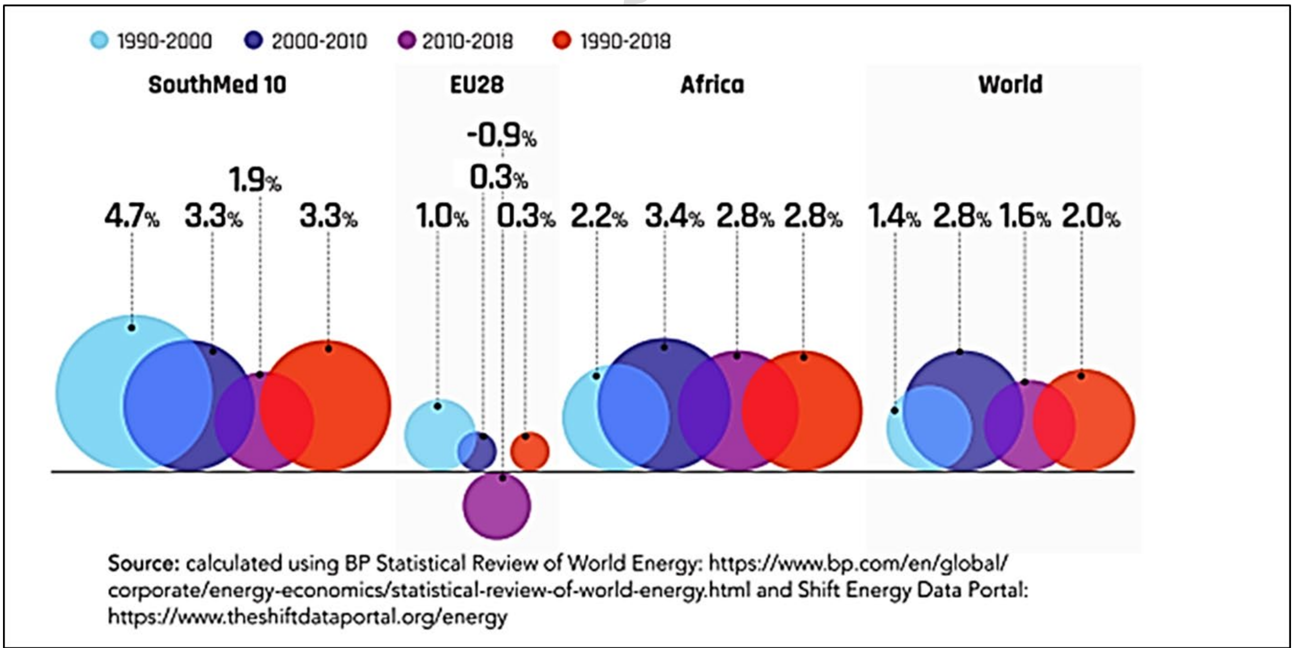

Figure 5.2 | Primary Energy Consumption, annual average growth rates, South/East Med and other regions. (Source: Moreno-Dodson et al. 2021)

5.3.1.2 Pathways for sustainable coastal tourism

The Mediterranean attracts about one third of world tourism and it was the main tourist destination in 2019 (Plan Bleu 2022). Coastal tourism worldwide is likely to reach 26% of the total ocean industry value-added in 2030, becoming the largest blue economy sector (OECD 2016) *(high confidence)*. At the same time, this type of tourism is among the most impacted sectors by climate change, especially in the Mediterranean Basin (UfM 2018; Tonazzini et al. 2019). Climate change has a significant impact on coastal ecosystems, as it causes modifications both on weather conditions and hydrodynamic processes (e.g., sea-level rise, water scarcity, coastal erosion, increase of storm surges, increase of frequency and height of tides). Major climate change impacts affecting Mediterranean tourism destinations include water scarcity, warmer summers, climate instability, marine and coastal biodiversity loss, and increase in disease outbreaks (Simpson et al. 2008). These impacts, although not yet perceived as relevant, are going to worsen in the mid and long-term future (UfM 2018) *(medium confidence).*

Climate and weather are important factors in tourists' decision-making, as well as safety, and influence the successful operation of tourism businesses (Gómez Martín, 2005; Becken 2010), destination choice and, as a consequence, tourist flows. Islands are particularly vulnerable to the above-mentioned risks because of their strong dependency on the ecosystem services provided directly (e.g., fish and seafood provision) and indirectly (coastal and maritime tourism) by the sea, together with natural resources and space constraints (Tonazzini et al. 2019). For instance, Mediterranean top tourism destinations such as Malta, Corsica, Balearic Islands, Sicily and Sardinia have been experiencing population congestion and over development in the last decades (Manera et al. 2016; Briguglio and Moncada 2020) *(high confidence).*

While NMCs are a rather mature tourism destination, some SMCs have only recently experienced a significant growth in coastal tourism (e.g., Egypt and Türkiye). One of the consequences of this is that most of the pressures associated with this economic sector tend to be stationary in the NMCs whereas there are likely to increase in the coming years in SMCs (Randone et al. 2017; Tonazzini et al. 2019). In addition, some Mediterranean Countries (Egypt, Israel, Jordan, Lebanon and Palestine) are likely to be most impacted by climate change in the medium (2030) and long term (2050) (UfM 2018) *(medium confidence).*

Since Mediterranean coastal tourism causes environmental and social impacts, which negatively affect its own existence with a loop effect (Randone et al. 2017; Drius et al. 2019a), there is an urgent need to reduce such impacts in the region in order to comply with the SDGs of the 2030 Agenda for Sustainable Development and the Mediterranean Strategy for Sustainable Development 2016–2025 (MSSD 2016–2025), specifically addressing measures that reduce the impacts of climate change *(high confidence)*. While it is not yet clear if with warmer temperature the overall number of tourists will increase (Katircioglu et al. 2019) or decrease (Torres et al. 2021), it is evident that national and regional authorities must put into place policies to adapt, for instance, to energy and water demand, which is likely going to increase. The SDGs explicitly related to coastal tourism are SDG 8 (Economic Growth), SDG 12 (Sustainable Consumption and Production) and SDG 14 (Ocean Conservation) *(medium confidence).*

Increasing attention has been paid to how climate change might impact tourist destinations (Wall and Badke 1994) and how these might adapt to minimise risks and maximise opportunities (Becken and Hay 2007). These challenges could be addressed by providing credible, comprehensible, diverse and replicable alternative tourism models (Randone et al. 2017) *(high confidence)*. One example in this sense is ecotourism, a sustainable alternative of the traditional tourism practices in coastal and maritime areas, which promotes local communities and the conservation of natural resources. This type of tourism is getting more popular even in the conventional tourism market (chain hotels, large resorts, premium cruise ships) (Tonazzini et al. 2019). Sustainable tourism models are also encouraged by various international organisations (e.g., UfM) and programmes (e.g., the Interreg MED Community "Sustainable tourism" financed by the European Union https://sustainable-tourism.interreg-med.eu/). Very recently, the Glasgow declaration for climate action in tourism has been receiving attention from public and private organisations, who commit to implement a series of actions to cut tourism emissions (One Planet Sustainable Tourism Programme, 2021) *(medium confidence).*

An additional pathway to coastal tourism sustainability could be a set of policy tools that national and local governments can use to facilitate sustainable tourism. These range from green taxes, directed to penalise practices that are harmful to the environment, to sustainable tourism indicators, to eco-labelling tourism schemes (Randone et al. 2017) *(high confidence)*. Many Mediterranean countries have developed their own Integrated Coastal Zone Management (ICZM) – a multidisciplinary and iterative process to promote sustainable management of coastal zones. Morocco, for instance, has put in place a series of measures to tackle coastal erosion, which have implications on tourism related infrastructure, such as removing beach sand and riverbed aggregates to be used as building materials; restricting the urbanization of the coasts; introducing beach monitoring programmes, protection and regeneration of some of the remaining dunes; and strengthening of watershed erosion protection programme through upstream of dams (UfM 2018) *(high confidence).*

5.3.1.3 Pathways for sustainable small-scale fisheries

Small-scale fisheries contribute significantly to the livelihoods and food security of coastal populations along the Mediterranean Sea (*high confidence*). Their contribution is crucially important to the more vulnerable populations, particularly in rural coastal communities. Small-scale fisheries represent over 84% of the total fishing fleet, employ nearly 62% of the total workforce on board fishing vessels, account for 29% of total revenues from marine capture fisheries, and claim 15% of the total catch (FAO 2020). The revenues are distributed disproportionately between small-scale fisheries and industrial fisheries, with significant variation across countries. For instance, the contribution of small-scale fisheries in France and Ukraine represents around 70% of total revenues from marine capture fisheries, whereas in Algeria, Egypt, Italy and Spain their share is below 20%. The contribution of small-scale fisheries to total employment ranges between 70 and 90 in Ukraine, Bulgaria, Greece, Lebanon, Slovenia, Cyprus, France, Croatia, Tunisia and Türkiye and between 25 and 35% in Algeria, Egypt and Spain (FAO 2020).

Over 80% of the fish stock in the Mediterranean is threatened by overfishing, sometimes at rates six times higher than the maximum sustainable yields (*high confidence*). A practice that is bound to reflect negatively on the small-scale fishers. The pathway to sustainable small-scale fisheries would require the meaningful participation of the small-scale fishers in the co-management of the sector to minimize the long-term impacts on the fish population and the livelihood of the fishing communities. Specific actions to control overfishing would include the promotion of best practices to maximize the value of the catch by directing fishing activities towards the catch of selective, high-value products and supporting fishers by creating vertically-integrated distribution channels (Randone, et al. 2017). Income diversification, through the creation of alternative job opportunities, would also contribute to the well-being of fishing communities. The Regional Plan of Action for Small-Scale Fisheries in the Mediterranean and the Black Sea (RPOA-SSF) recommends strengthening of the value chains, improving market access for small-scale fisheries products and increasing the profitability of the sector (FAO 2020).

5.3.2 Scenarios and pathways to achieve the Sustainable Development Goals (SDGs)

Sustainable development pathways are part of different scenario frameworks developed by the research community to describe major social, economic and environmental developments including in terms of climate change adaptation and mitigation. There are multiple possible pathways by which the Mediterranean region can pursue a sustainable and climate resilient development. There is robust evidence that current development pathways are leading away from sustainable development (IPCC 2022) *(high confidence).* On the other hand, pursuing sustainable development goals and climate resilience increases their effectiveness.

5.3.3 Best practices and successful case studies in the Mediterranean coastal areas

The case of cruising: pathways to sustainability?

Worldwide, the ocean cruise industry is one of the most dynamic segments of the tourism sector, concentrating more than 26.6 million passengers in 2017 (CLIA 2017). It is a highly impacting sector in terms of CO_2 emissions, from ship building till ship dismantling, as well as polluting harbours and their inhabitants (Lloret et al. 2022) *(high confidence)*. The actual cruise shipbuilding takes 2 to 3 years and should follow a technical measure for reducing CO_2 emissions, the Energy efficiency Design Index, whose requirements are tightened every five years (Tonazzini et al. 2019). When finally dismantled, the disposable vessels comprise a vast range of hazardous substances such as PCB, asbestos and waste oil products (Tonazzini et al. 2019) *(high confidence)*. Cruise ships in operation are the most carbon intensive means of transportation: according to Howitt et al. (2010) a journey ranges between 250 to 2200 g of CO_2 per passenger per kilometres. Cruise ships operate on fuels rich in carbon and sulphur and their engines are kept running close to city centres. In the Mediterranean Basin, cruise ship traffic is second only to the Caribbean, and it has been producing increasing air pollution in ports over recent years, with three top cruise terminals, in terms of emissions: Barcelona, Palma de Mallorca (Spain) and Venice (Italy) (Karanasiou, 2021) *(high confidence)*. The case of Venice has been largely studied, showing how cruise tourism is a complex issue in relation to sustainability, as many actors involved in the market identify benefits and costs (also in terms of environmental impacts) of the cruise industry in different ways (Asero and Skonieczny 2018). This considered, a long-term management strategy involving international agencies, cruise line operators and host communities seems to be a reasonable pathway towards sustainability. There is not any international coordination of the cruise industry at the regional level, which leaves the Mediterranean area open to exploitation (Asero and Skonieczny, 2018) *(medium confidence)*. A remarkable step for the reduction of the environmental impacts caused by the cruise industry was the very recent proposal to designate the Mediterranean Sea, as a whole, as an Emission Control Area (Hoenders 2022) *(medium confidence)*.

An increasing number of cruising companies voluntarily report on their environmental impact. However, those reports are often "self-assessments" and thus can be too focused on "soft" indicators, not always including full carbon footprint, quality of employment or human rights enforcement (Macneill and Wozniak 2018) *(medium confidence)*.

A concrete measure to reduce CO_2 emissions and air pollution is the electrification of ports, called Short-Side Electricity (SSE), also known as cold-ironing, which allows cruise ship operators to turn off the ship engines while in port (Oxford Economics 2021) *(high confidence)*. Winkel et al. (2016) found that SSE offers the potential to reduce CO_2 emissions by over 800,000 tons in Europe alone. This technology is currently available in few berths worldwide (64 in Europe; 9 in Asia), whereas only 25 cruise vessels are equipped with the necessary technology for shore power connection. The main disadvantages of the SSE are the relevant initial investments and the lack of know-how needed to let cruise lines and ports cooperate. In addition, the electricity provided should originate from renewable resources. SSE does not only address climate action (Sustainable Development Goal (SDG 13), but encompasses a variety of nine SDGs: SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG9 (industry, innovation and infrastructure), SDG11 (sustainable cities and communities), SDG 13 (climate action), SDG 14 (life below water), and SDG 15 (life on land) (Stolz et al. 2021) *(high confidence).*

Cruise ships or rather cruising is also associated with luxury, excessive consumption and therefore wastage. This relates to the diversity of products made available to passengers (Wysocki 2001). Cruise ship tourism is also gaining in popularity with movements within the Mediterranean tripling in the last decade with each itinerary consisting of 13,194 stops at different ports of call (MedCruise 2016) *(high confidence)*. The average dimension of a cruise ship is 200 m long, 26 m beam and a passenger capacity of 3220 people. This marks a shift from the early 2000, where the ships carrying more than 2000 people were very few (Pallis 2015). In fact, these ships can well compare to 'floating cities' resulting in the generation of large waste volumes which includes sewage, wastewater from bathrooms, hazardous waste, solid waste, oils etc. (Congressial Research Service 2010). Garbage reception facilities are therefore a necessity in ports with containers being the basic storage facility offered for most waste except cooking oil. However, segregation of waste is limited in view that the majority of ports of call assign this job to an external contractor with most waste ending in landfill (82%), followed by recycling (71%). The latter relates to plastic waste whereby 80% of Mediterranean cruise ports recycle plastic garbage (Pallis, 2017) *(high confidence)*.

5.3.4 Transformative pathway for sustainable development

Seeking new path for world' prosperity

The SDGs aim at shaping most of the world's major priorities for livelihoods. The objectives embedded in the SDGs' were ambitious and wide, ranging from the elimination of extreme poverty to major reductions in inequality and switching course to protection of nature. Ambitious climate policies, as well as economic development, education, technological progress and less resource-intensive lifestyles, are crucial elements for progress towards the main aims of SDGs. However, using an integrated modelling framework covering 56 indicators or proxies across all 17 SDGs might be insufficient to reach the global targets (Soergel et al. 2021).

Transformations to achieve the SDGs and challenges

Indeed, the need for transformational schemes is a pressing concern. Achieving the 17 SDGs Goals and the goals included in the 2015 Paris Agreement is challenging and complex. However, prioritising the following six major societal transformations can foster the attainment of those goals: quality education (SDG 4); access to good quality and affordable health care (SDG 3); renewable energy, and a circular economy (SDGs 7, 12, and 13); sustainable land and marine management (SDGs 2, 14, and 15); sustainable urban infrastructure (SDGs 6, 9, and 11); and universal access to digital services (SDG 9). In this context cooperation among actors and partnerships to achieve all goals (SDG 17), acquires an even more important role. Each transformation contributes to several SDGs and describes a significant change in the social, economic, political, technological texture to achieve sustainable development over the long term. Dropping any of them will make achieving the SDGs even more challenging. The six transformations can be implemented in every country to help address trade-offs and synergies across the SDGs (Sachs et al. 2019; Jeffrey et al. 2019).

The six societal transformations operate at the global, regional, and national levels. They must be adapted to country contexts, such as levels of development, natural resource base, and ecosystem governance challenges and structures. Each of the six transformations requires a significant scaling-up of public investments, and coordination among public and private authorities and civil society. However, the financing needs for SDG investments are far greater than the fiscal space available to governments of low-income developing countries (Sustainable Development Report 2021).

Transformations pathway for Climate Resilience

Transformative actions are increasingly urgent across all sectors, systems, and scales to avoid exacerbating the risks of climate change, and to meet the SDG's goals. In the context of climate resilient pathways, transformative actions concern leveraging change in the five pillars of development that drive societal choices, and climate actions, toward sustainability such as, social cohesion and equity, individual and agency, and knowledge developments have been identified as steps to transform practices and governance systems for increased resilience. However, in some cases, transformative actions face resistance from the political, social, and/or technical systems and structures they are attempting to transform. There is mounting evidence that many adaptation efforts have failed to be transformative, but instead increased inequality and imbalance, especially when following too strictly free market measures. Thus, marginalised and vulnerable groups would need to be placed at the centre of adaptation planning (Veland et al. 2021).

[Start Box 5.1 here]

Box 5.1: The transformation capacity of sustainable development pathways

There are over ten years to achieve the Sustainable Development agenda 2030. However, most countries still need to adequately satisfy basic human needs on a global and sustainable level of resource use.

Countries need to be closer to the overarching goal of balancing human well-being with a healthy environment. Each country must respond to its circumstances and priorities while moving away from current practices of growing first and cleaning up later. The comprehensive transformation towards sustainable development in the coming decade depends on simultaneously achieving innovative country-specific pathways.

However, human well-being need not depend on the intensive use of resources, nor need it to exacerbate or perpetuate inequality and deprivation. Scientific knowledge allows the identification of critical pathways that break this pattern, and numerous examples from around the world show that this is possible.

The way forward to advance the 2030 Agenda must include an urgent and deliberate transformation of science-policy, social and ecological-economic systems, differentiated across countries but adding to desired regional and global outcomes to ensure human well-being, community health and limited environmental impact. Achieving this transformation is a profound and deliberate departure from business as usual to systemic interactions and cascading effects, as working toward one goal can alter the possibilities for meeting other goals.

Furthermore, new scientific and technological research and the adaptation of existing knowledge and technologies to specific local and regional contexts are needed to streamline efforts further and maximize synergies between all goals to proactively accommodate emerging challenges after the 2030 horizon (Global Sustainable Development Report, UN 2019).

[End Box 5.1 here]

5.4 Social equity and climate justice

5.4.1 The links between social inequalities and sustainable pathways in coastal communities

The social and economic characteristics of coastal communities differ greatly across the Mediterranean Basin. These are informed by a clear difference in the levels of human development, as captured by the Human Development Index (HDI), ranging from a ranking of 155th (over 189 countries) for The Syrian Arab Republic, and 121st for Morocco, to the very high development of Israel (19th) and Slovenia (22nd), or in the levels of per-capita wealth, ranging from the 3613 USD Gross National Income (GNI) of Syria to the 42,766 USD of Italy (UNDP 2020). The HDI for 2018 presented in the First Mediterranean Report 2020 provides similar ranking trends with Syria (154th), Morocco (121st), Israel (22nd) and Slovenia (24th). Historical events, among which colonisation and conflicts, have also played a major role in shaping the current levels of wellbeing, governance, and social status of many citizens across the Mediterranean (Gürlük, 2009). Furthermore, economic policies that prioritised strict macroeconomic balancing measures and short-term gains for a selected number of stakeholders, at the expense of long-term sustainable development for a larger part of society, are also responsible for growing social inequalities in the

Mediterranean area (Lehndorff, 2012). Examples in this domain can be found in the excessive privatisation of health and education services, which, when faced with a crisis like the COVID-19 Pandemic, brought many countries (Assa and Calderon, 2020) to understand that the original gains obtained from the budget cuts were overwhelmingly outweighed by the costs incurred to deal with the emergency, made worse by the lack of preparedness often linked to reduction in budgets for those crucial sectors (Williams 2020) *(medium confidence)*.

Climate change is adding a further layer of constraints to existing social inequalities, especially on women, the elderly and children (Ali et al. 2022). Young people, being the fastest growing population in the Eastern and Southern Mediterranean Region are potentially the most affected by climate change. Infants and children are less able to survive extreme weather events and diseases, particularly those living in poverty and experiencing displacement (Al-Jawaldeh et al. 2022). In recent years, coastal communities have experienced an increasingly higher level of social inequalities, which, besides cyclical socio-economic drivers, tend to be more pronounced due to the specific pressure that climate change events are exerting on coastal areas (Lionello et al. 2021). The capacity to respond to climate change events, and more general disasters, is often linked to development levels, with the assumption that the higher the wealth and the lower social inequalities are, the better the capacity to cope in the short term, and adapt in the long run (Briguglio, 2016). Therefore, existing social inequalities can act as a further barrier to climate change adaptation, and more generally to sustainable development pathways. Addressing social inequalities among coastal communities can therefore be an important tool to promote better adaptation and ensure sustainable development pathways (Cinner et al. 2018) *(high confidence)*.

To this end, it is crucial to identify a number of best practices in Mediterranean countries that while reducing social inequalities can support post-pandemic climate resilient socio-economic systems. Among these the use of economic instruments, such as taxation, subsidies, play a central role to support the most vulnerable categories (Panaiotoiv, 1994; Bräuninger et al. 2011). These results have the potential to also be scaled-up to other countries in the Mediterranean Basin. For this to happen, however, besides forward-looking policy making, there must be an opportunity to improve existing gaps in data collection within and among countries in the Mediterranean Basin, thus providing policy with data that can drive policy models potentially in many settings *(medium confidence)*.

5.4.2 Access to social infrastructure

Social infrastructures include health, educational, cultural and environmental factors that enhance social comfort (Torrisi, 2009). Availability of, and access to, social infrastructures such as schools, hospitals, green areas, and cultural spaces are among the standard indicators of the quality of life of a country. Poor healthcare, cultural services and education affect the bad placement of Mediterranean cities, such as Algiers, Tripoli and Damascus in the Global Liveability Index (EUI 2022). The COVID-19 pandemic also drove a move down in the ranking of some European Mediterranean cities, such as Barcelona, which, in 2022 only, fell 19 places. Social infrastructures have also positive impacts on social cohesion, by ensuring equal access to basic services (such as health care and education) across cities and regions (OECD 2021) *(high confidence)*. On the other hand, existing disparities in access to social infrastructures can exacerbate pre-existing inequality within and among countries and undermine social cohesion. In the EU, the importance of bridging critical social infrastructure gaps to ensure a sustainable and climate resilient development has been emphasised in the aftermath of the COVID-19 pandemic, when in several countries, including European Mediterranean countries, such as Slovenia and Greece, over 50% of households were at risk of descending into poverty (CEB 2020). Here, investments in social infrastructures, such as schools, health and social care services can help to advance several SDGs, including SDG3 (health), SDG4 (education) and SDG5 (gender equality). According to a recent OECD study (OECD 2020), only a few regions in the OECD area have achieved the outcomes suggested for SDG3 and SDG4, with large inequalities existing within countries, including Mediterranean countries, such as France and Spain. For SDG4, for example, while the Basque country has achieved the end value for the used indicators (i.e., bring school dropouts to 8% or lower and tertiary education to at least 46% of the adult population), the Balearic Islands are halfway to meeting it *(medium confidence)*.

In terms of gender equality, where the indicators used for SDG5 are: same employment rate and part-time employment for both women and men, the Mediterranean countries with largest regional disparities are Türkiye and Israel (OECD 2020). Here, Eastern Anatolia E. and North Israel are the two farthest regions to the end values in the respective country, while the capital regions (Eastern Blak Sea and Tel Aviv) are the best performing regions. However, the country that displays the largest disparities in employment for women and men across its cities is Italy, with the coastal city of Venice facing one of the largest possible distances to the end value for SDG5 *(medium confidence)*.

5.4.3 Inclusion

Social inclusion is a context-dependent concept (Silver 2015) which depends on several factors including availability of resources, mechanisms and processes that enhance people's capabilities and opportunities to participate in economic, social, cultural and political arenas. Being multidimensional and dynamic, social inclusion can be hardly measured, especially when standard data sources across countries are lacking (UN 2016). With respect to the Mediterranean, available literature (e.g., UN 2016; Capasso et al. 2018) shows that lack of social protection, informal and insecure employment and high numbers of young people not completing secondary education affect particularly the Southern and Eastern Mediterranean (SEM) countries (Egypt, Tunisia, Morocco, Palestine, Türkiye and Lebanon), and especially young women (Murphy 2018) *(high confidence*). In these countries, and principally in Egypt, relatively higher income inequality has also been observed (Alvaredo and Piketty 2014; Alvaredo et al. 2018). Also, European Mediterranean countries, which are generally more inclusive, if compared with Northern European countries show limited welfare protection and greater socioeconomic inequalities (Conde-Sala et al. 2016) *(medium confidence)*.

Both in Northern and Southern Mediterranean countries segregation and disempowerment of migrants, due to informal work arrangements and little or absent union activity, limit social inclusion, especially of some groups, such as agricultural workers. This notwithstanding, and although youth unemployment is higher in Southern European cities than in some SEM countries (e.g., in Moroccan cities, Surian-Sciandra 2019) the share of young people (15 to 34-year-olds) migrating or willing to migrate from SEM towards EU countries increased over the past decades, and particularly in the aftermath of the Arab uprisings (De Bel-Air 2016). In 2020, Moroccans were the largest group among new EU citizens (EUROSTAT 2021) and the largest number of migrants from Africa leaving abroad, after Egyptians (McAuliffe-Triandafyllidou 2021). Yet, despite being relatively better integrated in their destination countries than other foreign immigrant communities, their cultural integration remains low (e.g., in Italy: Di Bartolomeo et al. 2015) *(high confidence)*.

Climate change can be a driver of social inclusion in so far it urges cities and communities to interconnect and address together the common challenges of climate change, for example by promoting common cultural heritages, including the Mediterranean diet (Tarsitano et al. 2019) *(low confidence)*.

However, climate change impacts can also be a limit to social inclusion: the main economic sectors in the Mediterranean region, including fisheries and agriculture, are highly vulnerable to climate-related risks (such as flooding, storms, heatwaves and sea-level rise) and coastal communities and ecosystems are among the most negatively impacted by these impacts. Projected increase in climate hazards in the Mediterranean region can put at risk marine species and coastal systems with limited adaptation options, especially in SEM countries (Linares et al. 2020), where capacity to adapt is minor and decreases in food production on land and from the sea can affect income, livelihoods and food security, and further erodes people's economic and social rights *(medium confidence)*.

Yet, as the WG2 contribution to the Sixth IPCC Report (IPCC 2022) discussed it, social processes can promote transformative adaptation, including in the Mediterranean Basin, where the implementation of institutional frameworks can enhance human rights protection and reduce risks of conflict, displacement and human insecurity (*high confidence*). Inclusive and participatory approaches exist in Mediterranean countries, as documented for example in the water sector by Iglesias and Garrote (2015) and can be used to promote climate resilient sustainable development pathways in the region. In coastal community's adaptation responses to climate change have been taken in the forms of structural defence, ecosystem protection and restoration and livelihood diversifications; but often with negative gender outcomes that lead to an exacerbation of inequalities (Prakash et. al., 2022) and negatively impact the attainment of SDG 5 for gender equality *(medium confidence)*.

As the SROCC has highlighted (IPCC 2019), densely populated coastal zones are places at risk particularly for women and girls, since they have less access than men and boys to information and training on disaster preparedness and response (*high confidence*). However, there is a lack of studies focused on gender in the context of coastal hazards in the Mediterranean region, which generates a gap of knowledge in this respect.

5.4.4 Gender, climate justice and transformative pathways

Gender, inclusion, and equality issues are important for transformation pathways to climate resilient development. A gender term herein does not centre only on women or men but examines structures, processes, and relationships of power between and among groups of men and women and how gender interacts with socio-economic status, nationality, or education to create multidimensional inequalities (Hopkins 2019) *(medium confidence).*

Thus, the transformative pathways highlighting the unequal distribution of climate change impacts and opportunities for adaptation and mitigation, climate justice for human and ecological well-being, aim to address the importance of equitable participation in environmental decision-making for climate justice leading to changing structural inequalities.

Achieving the SDGs means positive sustainability and quality development processes and procedures. Gender, inclusion, social justice, well-being and equity enable a sustainable and long-term course of Climate Resilient Development pathways. Hence, the relationship between adaptation and the SDGs would be represented in the achievement of SDG 3 for Good health and well-being, SDG 5 for Gender equality, SDG 16, Peace, Justice and Strong Institutions, and SDG 17, Global Partnership for Sustainable Development. The SDGs are the foundation of social justice and equity that underpin sustainability outcomes and enable the development of resilience to climate change *(medium confidence).*

The main question is to what extent the implementation or non-implementation of adaptation measures can contribute to, or undermine, the achievement of the sustainable development goals, in particular by equity participation in development processes and in the political, economic, environmental, social, ethical, and thus contribute to CRD pathways *(low confidence)*.

5.4.5 Diversity

Diversity in natural and human systems is an inescapable fact due to variability among living organisms and conditions. When it comes to social equity and climate justice the concept of diversity is preferable to uniformity as the effects of climate change are not evenly felt across populations and also the ability to adapt varies across different countries and sectors of society. Therefore, response capacity to climate change impacts must be increased, and resources concentrated, where vulnerability to climate change is higher.

In the Mediterranean region, differences exist originating from biological diversity and socio-cultural richness, but also from diverse socio-economic and human development conditions (with some countries, such as Israel and the EU Mediterranean countries in the highest human development category and others, such as Syria, in the lowest) (HDI 2020; MedECC 2020).

In this context, climate change, in combination with other global change drivers, such as urbanisation and rural exodus, is a threat for the diversity of Mediterranean marine and coastal ecosystems (Cramer et al. 2018), exacerbating degradation of coastal zones due to other concomitant socio-economic factors, such as coastal population growth and tourism (Senouci and Taibi 2019; Petrisor et al. 2020). Based on regionalized Shared Socioeconomic Pathways (SSP), the assessment of future impacts in coastal zones of the Mediterranean region varies depending on several factors, including local migration policies, shipping, tourism and fishing activities, and high urbanisation rates (Reimann et al., 2018). In these zones sustainable development pathways are based on policies that reduce the number of people impacted by coastal hazards, improve low living standards, and increase adaptive capacity (Reimann et al. 2018) *(medium confidence)*.

5.4.6 Access to climate finance funds

There are different challenges linked to obtaining access to climate finance, especially when zooming in specific parts of a country, such as coastal areas. For instance, large scale infrastructure projects, mainly for mitigation purposes, are more successful in attracting funding than do small-scale adaptation projects at local levels (Costa et al. 2022) *(medium confidence)*. The main challenge for the Mediterranean region, especially the Southern and Eastern Mediterranean region (SEMed), is upscaling the level of funds available to meet the urgent financing needs to support sustainable pathways toward a climate transition. Most of the funds are driven by public sector initiatives with minimal, or little effort, by the private sector, with only Egypt issuing green bonds to date (Costa et al. 2022), therefore limiting the mobilisation of private funds that can support the need to achieve an effective transformative and sustainable change. The UNFCCC defines climate finance as "local, national, or transnational financing—drawn from public, private, and alternative sources of financing—that seeks to support mitigation and adaptation actions that will address climate change." (UNFCCC 2022). Climate finance refers to the investments necessary to transition the world's economy to a low-carbon path, to reduce greenhouse gas concentrations levels, and to build resilience of countries to climate change (Hong et al. 2022). The EU Med countries are viewed as leaders and pioneers of green finance, with an important developing market whereas the SEMed countries are struggling with inadequate flows of funds sufficient to make a transition towards a green economy to fulfil the objectives of the Paris Agreement (Costa et al. 2022) *(medium confidence)*.

In accordance with the principle of "common but differentiated responsibility and respective capabilities", Annex I countries are to provide financial resources to assist non-Annex I countries in implementing the objectives of the UNFCCC. International climate finance commitments to the SEMed region accounted for 11% of global financial flow in 2019, amounting to USD 9.12 billion, with bilateral donations comprising around 37% of the overall amount (UfM 2022). Major bilateral donors include the EU institutions (excluding EIB), France and Germany. Multilateral climate funds provided the smallest share of overall climate finance to the SEMed region with only 2%. SEMed countries differ in their abilities to access climate funding, with Türkiye, Egypt and Morocco being most successful, while the other countries such as Jordan, Syria, Libya, Algeria and Montenegro witnessing difficulties (Midgley et al. 2016) *(medium confidence)*.

Alternative scenarios, ranging from all green, shades of green, brown (finance as usual), and crisis and conflicts, for the future of green and climate finance will likely produce dramatically different outcomes depending on political, regulatory and market factors (Costa et al 2022). The all green scenario entails NMCs step up their financial commitments and deliver beyond their pledges to provide sustainable finance to SEMed countries in addition to fostering Euro-Mediterranean cooperation to develop a common strategy and knowledge sharing, and establish common standards and reporting measures. The SEMed countries, in turn, institute reforms to improve the business environment and allow the use of innovative instruments such as green bonds, guarantees and public-equity co-investments, among others, to ensure the flexibility and attractiveness of green and climate finance. The all green scenario will produce large, bankable and transformative projects in the energy, building and transport sectors across the Mediterranean. In parallel, green finance reaches small projects benefiting local communities and creating decent and sustainable jobs, contributing to a fair and just transition (Costa et al. 2022) *(medium confidence)*. According to Climate Policy Initiative (2021), global climate finance flows reached USD 632 billion in 2019/2020 recording a timid 10% increase relative to the average increase of 24% in previous periods; however, to meet climate objectives by 2030, annual climate finance must increase by at least 590% to USD 4.35 trillion in order to maintain a 1.5-degree pathway (*high confidence*).

Table 5.5 | Environment, Social, and Governance (ESG) Risk Ratings in the Mediterranean Source: Economic Intelligence Unit (EIU) (March 31, 2022) (https://www.eiu.com/n/solutions/esg-rating-service/?utm_source=mkt-content&utm_medium=email&utm_campaign=esg-rating-service-map-june-22&mkt_tok=NzUzLVJJUS00MzgAAAGE5iC9gS4_FIv0ktCjIJDwI7oGA9p1AYWNd_BC3GDRB4BqGhC4_glouDcoBUnaEYDTlH9mKFJQwdPOecLx65IKd06upBnKstat2PCvHyGbS2702Q (Accessed on June 13, 2022)

EIU's Environment, Social, and Governance (ESG) Risk Ratings				
Country	**Overall Assessment**	**Environment**	**Social**	**Governance**
Albania	No Data	No Data	No Data	No Data
Algeria	High	High	High	High
Bosnia and Herzegovina	No Data	No Data	No Data	No Data
Croatia	Low	Low	Low	Low
Cyprus	Low	Low	Low	Low
Egypt	High	Moderate	Very High	High
France	Very Low	Very Low	Low	Very Low
Greece	Low	Very Low	Low	Low
Israel	Low	Moderate	Low	Low
Italy	Low	Low	Low	Low
Lebanon	High	High	Moderate	High
Libya	No Data	No Data	No Data	No Data
Malta	No Data	No Data	No Data	No Data
Monaco	No Data	No Data	No Data	No Data
Montenegro	Moderate	High	Low	Moderate
Morocco	Moderate	Moderate	Moderate	Moderate
Slovenia	Very Low	Very Low	Very Low	Low
Spain	Very Low	Low	Very low	Very low
Syria	No Data	No Data	No Data	No Data
Tunisia	Moderate	Moderate	Moderate	Moderate
Türkiye	High	Moderate	High	Moderate

[Start Box 5.2 here]

Box 5.2: Capacity building and knowledge transfer for sustainable development

Capacity building is an essential catalyst to sustainable development and human welfare on the planet, it is essential for enabling all countries to benefit from all-natural resources and conserve their future. Capacity Building (CB) is an important part of the means to implement the Sustainable Development Goals (SDG 2030, para. 41). Each of the SDGs contains targets related to the means of implementation, including capacity building; for example, SDG 17 which covers the means of implementation and the global partnership for sustainable development, contains Goal 17.9 which aims to: "Strengthen international support for the implementation of effective and targeted capacity building in developing countries to support national plans to implement all development goals, Including through North-South cooperation, South-South cooperation and triangular cooperation.

What does capacity building mean? How best to define it?

Capacity building (or capacity development, or capacity strengthening) is the improvement of an individual, organisation, or country's ability to produce, perform, or deploy. The terms capacity building and capacity development are often used interchangeably. OECD-DAC 2006, stated that capacity development is the preferred term.

The general definition of capacity development is "Capacity development is a transformative approach that enables individuals, leaders, organisations and societies to acquire, strengthen and maintain capabilities to set and achieve their own development goals over time. Simply put, if capacity is the means to plan and accomplish, then Capacity development describes the methods of those means Capacity development refers not only to the acquisition of new knowledge and skills, but also above all to the change of values and behavioural patterns (UNEP 2015).

Capacity building is one of the boundless terms most often used to describe the distance between developed and developing countries. It is very rich and complex and is undoubtedly a prerequisite for saving our planet. However, it is usually underestimated and implemented in an inefficient and traditional "business as usual" scenario

Historical context

Capacity building has long been recognized as one of the means of implementation for the achievement of sustainable development action plans and development strategies. Agenda 21, adopted at the 1992 United Nations Conference on Environment and Development, addresses capacity-building in its Chapter 37. Decisions relating to capacity-building were taken by the United Nations Commission on Sustainable Development at its fourth (1996), fifth (1997) and sixth (1998) sessions and by the United Nations General Assembly at its Special Session to review the implementation of Agenda 21 (1997).

The Johannesburg Plan of Implementation (JPOI), adopted at the 2002 World Summit on Sustainable Development also recognized the importance of capacity-building for the achievement of sustainable development. Similarly, the outcome document of the Rio +20 Conference, the Future We Want, emphasised the need for enhanced capacity-building for sustainable-development and for the strengthening of technical and scientific cooperation. Capacity Development is also recognized as a key issue in the 2014 SAMOA Pathway for a wide range of areas, such as climate change, sustainable energy, ocean sustainability, management of chemicals and waste as well as financing.

UNDP integrates this capacity building system into its work on reaching the Millennium Development Goals (MDGs). It focuses on building capacity at the institutional level because it believes that "institutions are at the heart of human development, and that when they are able to perform better, sustain that performance over time, and manage 'shocks' to the system, they can contribute more meaningfully to the achievement of national human development goals." (source: United Nations Development Programme. "Supporting Capacity")

In the context of restoration and conservation the world ocean and coasts; the UN Ocean Decade for sustainable Development (2021–2030) Implementation Plan (IP) recognizes capacity development as an essential tenet to achieving evenly distributed capacity across the globe, across generations, and across genders and thus reversing asymmetry in knowledge, skills and access to technology.

Capacity-building as a transformative system for world's climate-environment Risk management

One of the most pressing challenges in the world is coastal urbanization, impacting the wellbeing of ecosystems, with climate change exacerbating this process, thus the need for advanced knowledge and capacities to deal with coastal inundation, coastal pollution and multi-hazards. Ocean acidification and climate change caused by ocean absorption of anthropogenic carbon dioxide from the atmosphere, and acidification of ocean surface waters, mostly due to carbon dioxide emissions, can severely threaten the existence of various marine species. Since the mid-19th century, sea level has risen, as a result of human-induced climate change. A number of coastal cities and coastal resources are becoming heavily impacted by sea level change.

Within the Mediterranean Sea national, regional and international entities have launched many effective initiatives for global coastal observation, prediction and scientific capacity development for the Decade. However, we should go beyond scientific capacity development, by creating a new awareness at the policy and civil society level, identifying alternative solutions and reducing fragmentation and facilitating cooperation between countries. The effective use of unprecedented achievements in capacity development, is indispensable to ensure that growing development demands and a sustainable healthy ocean coexist in harmony.

[End box 5.2 here]

5.5 Knowledge gaps (or 'Final remarks')

- Further research is needed in the area of sustainable energy transition, where gaps exist to identify current energy needs, also in the light of the increasing electrification of transportation fleets, and the socioeconomic categories most at risk when measures are implemented to achieve such a transition
- To support a faster and equitable transition to sustainable development pathways, we must increase investments in research and development to identify the right mix in the use of:
    - command and control (laws, regulations, etc);
    - economic instruments (taxes, subsidies, cap-and-trade, etc);
    - private mechanism;
    - education and awareness.

These are essential tools to guide policy in the adoption of evidence-based measures.

- New and additional resources are needed to support ongoing research in ecosystem and nature-based solutions, especially blue carbon sinks (seagrass meadows, marshes, etc), to promote sustainable development pathways, especially through the following activities:
    - conservation;
    - management;
    - restoration

In this sense, strengthening coordination and cooperation between Mediterranean countries and actors would be vital to advance knowledge in an area that both supports and provides livelihoods in many coastal Mediterranean areas.

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