

The Mediterranean Sea we want

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ABSTRACT

This paper presents major gaps and challenges for implementing the UN Decade of Ocean Science for Sustainable Development (2021-2030) in the Mediterranean region. The authors make recommendations on the scientific knowledge needs and co-design actions identified during two consultations, part of the Decade preparatory-phase, framing them in the Mediterranean Sea's unique environmental and socio-economic perspectives. According to the 'Mediterranean State of the Environment and Development Report 2020' by the United Nations Environment Programme Mediterranean Action Plan and despite notable progress, the Mediterranean region is not on track to achieve and fully implement the Sustainable Development Goals of Agenda 2030. Key factors are the cumulative effect of multiple human-induced pressures that threaten the ecosystem resources and services in the global change scenario. The basin, identified as a climate change vulnerability hotspot, is exposed to pollution and rising impacts of climate change. This affects mainly the coastal zones, at increasing risk of extreme events and their negative effects of unsustainable management of key economic assets. Transitioning to a sustainable blue economy is the key for the marine environment's health and the nourishment of future generations. This challenging context, offering the opportunity of enhancing the knowledge to define science-based measures as well as narrowing the gaps between the Northern and Southern shores, calls for a joint (re)action. The paper reviews the state of the art of Mediterranean Sea science knowledge, sets of trends, capacity development needs, specific challenges, and recommendations for each Decade's societal outcome. In the conclusions, the proposal for a Mediterranean regional programme in the framework of the Ocean Decade is addressed. The core objective relies on integrating and improving the existing ocean-knowledge, Ocean Literacy, and ocean observing capacities building on international cooperation to reach the "Mediterranean Sea that we want".

Descriptors: Ocean Decade, Mediterranean Sea, Sustainable Development Goals, Marine science, Co-design.

INTRODUCTION

The Mediterranean Sea is a mid-latitude semi-enclosed marginal sea where many fundamental processes that characterize the general circulation of the world ocean also occur identically or analogously. The direct consequence is that the Mediterranean Sea can be considered as a "small-scale ocean" and a natural laboratory where field and numerical experiments as well as new strategies can be conducted in more favorable dimensional and environmental conditions. The basin, located at the border between two climate regimes, is disproportionately impacted by climate change: the Mediterranean currently warms at a rate of 20% faster than the rest of the globe (Lionello and Scarascia, 2018; Pisano et al., 2020, Cheng et al., 2021), thus experiencing dramatic changes that encompass the whole water column and menace the coastal zone at many levels of complexity (Cramer et al., 2018). Higher temperatures, as well as changes in precipitation patterns, runoffs, and storm regimes, coastal inundation and erosion,

saltwater intrusion into freshwater aquifers, higher storm-surge flooding, loss of habitats, changes in nutrient concentrations, and displacement of lowlands/wetlands are spreading the invasions of alien species. Furthermore, ocean acidification is endangering the life of many species, especially those producing hard shells and skeletons (Lemasson et al., 2017; Hoegh-Guldberg et al., 2017). The unique biodiversity of the basin is at stake.

Faced by three different continents, the Mediterranean is a vital source of nourishment and services that directly supports the livelihood of about 500 million people, especially in the poorest countries, and indirectly of the global population, essentially through maritime traffic and the attraction of tourism. Besides the environmental changes, the region is also undergoing intensive demographic, social, cultural, and economic changes. In this framework, the traditional knowledge, traditional technology, and customs contribute to guarantee the biodiversity, as recognized by the United Nations (Kang-Hyun Joo, 2019). Population growth combined with the growth

of coastal urban hubs is generating multiple environmental pressures stemming from increased demand for water, food, and energy resources, air and water pollution caused by wastewater discharge or sewage overflows, waste generation, land consumption and degradation of habitats, unsustainable use of living resources, landscapes, and coastlines. These pressures are further amplified by tourism, often concentrated in the Mediterranean coastal areas, and by the climate breakdown. No single discipline can be sufficient to unfold this complexity nor decoupling of scientific and humanistic culture can be further accepted to finally envision a sustainable, safe, depolluted and productive Mediterranean Sea - part of the Earth's Ocean and climate system thus fully implement Sustainable Development Goals (SDGs). The interconnectedness of science, culture, environment, economy, history and local knowledge is the key to tackle the challenges ahead and should be promoted by means of societal engagement. In this framework, from local and national to global level, Ocean Literacy enables bridging science with policy and society on relevant topics of ocean sustainability, observations and research (Eparikhina et al., 2021) and supports mutual nurturing of culture and science.

Multilateral international research on marine science in the Mediterranean has been promoted in the last century creating a well-established cooperation among scientific and research institutions. From this collaboration and further engaging key stakeholders at policy, private, and societal levels all along the services' chain, from upstream to intermediate to downstream, the Mediterranean regional observing and forecasting systems have been developed in order to provide systematic and long-term routine ocean data and products available for their rapid interpretation and dissemination. On the other end, an Action Plan for the Protection of the Marine Environment and the Sustainable Development of the Coastal Areas of the Mediterranean has been established under the United Nations Environment Programme (UNEP/MAP), as a regional cooperation platform and a multi-institutional framework for cooperation in addressing common challenges of marine environmental degradation. More recently, in the framework of the BlueMed Research & Innovation Initiative (hereafter BlueMed Initiative), a shared vision to foster blue jobs

and economy in the area was advanced, recognizing the value and role of science in supporting sustainable human activities at sea.

These multi-national well established collaboration framework will constitute the building blocks to reinforce the collaboration between science, policy makers, environmental agencies and economy actors and to proceed to further engagement of key stakeholders at policy, private, and societal levels.

Therefore, since the launch of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), a global framework to help generate ocean science solutions to key societal challenges and underpin the global Agenda 2030 (Ryabinin et al., 2019), the Mediterranean Sea has been recognized as a key component for the culture, development and economy of Europe, North African and Middle East countries and for the high potential of "*transformative change*" towards a sustainable future in a region.

In this view, two regional consultations, hosted by the Italian Oceanographic Commission (COI) and co-organised with the Intergovernmental Oceanographic Commission of UNESCO (IOC), UNEP/MAP, Mediterranean Science Commission (CIESM), European Commission (EC) with the support of the BlueMed Initiative, have been conducted between January and November 2020, as part of the preparatory activities of the Decade.

"*The Mediterranean Sea We Need for the Future We Want*" workshop, held on 21-23 January 2020 at the IOC Office in Venice (Italy), brought together 159 experts from 32 countries as well as intergovernmental and international organizations and networks to discuss the Mediterranean Sea perspective in the light of the Decade's societal outcomes: a clean ocean, a healthy and resilient ocean, a predicted ocean, a safe ocean, a sustainably harvested and productive ocean, a transparent and accessible ocean, and an inspiring and engaging ocean (see www.oceandecade.org). The meeting facilitated regional and interdisciplinary discussions across sectors, providing the added-value of alignment and coordination of the scientific communities across all geographical regions surrounding the basin, and stakeholders across several key sectors of activities, bringing together the voices of the Mediterranean at the global level (Capasso et al., 2020).

The virtual session “Co-designing the science and capacity we need for the Mediterranean Region”, held on 11 November 2020 with the support of the Swedish Ministry of the Environment, gathered in remote in the middle of the pandemic 237 experts from 48 countries and more than 100 international organizations ranging from ocean and transdisciplinary research institutions, United Nations (UN) partners and Non-Governmental Organizations (NGOs) to the private sector, with the common objective to share lessons of relevant Mediterranean experiences in order to co-design the Decade actions. A synoptic view of the scientific and capacity development priorities resulting from regional consultations is available in Table 1. It has to be noted that while the attempt to reach different stakeholders to prepare the Decade activities proved successful, the variety of the engagement should be better balanced, e.g., in order

to reflect the actual contribution of the private sector into relevant aspects of the blue economy. To close this gap, the role of National Decade Committees established at country level according to the principle of bringing all sectors of society as outlined in the Decade Implementation Plan (IOC, 2020) would be pivotal.

Driven by the UN Ocean Decade vision and Implementation Plan (IOC, 2020), the objective of this paper is to present the outcomes of these regional consultations as a new milestone towards an integrated, co-designed, and long-term strategic initiative to be developed in the Mediterranean, underpinning the Decade’s implementation. Specific priorities are identified by declining them in the perspective of a sustainable Mediterranean Sea, whose peculiarity results both from physiographic conditions and historical and societal developments.

Table 1. Scientific and Capacity development priorities for the Mediterranean Region (IOC, 2021).

| | | |
|--|---|--|
| Scientific priorities | A clean ocean | <ul style="list-style-type: none"> • Strengthen regional assessments and marine litter monitoring plans • Upscale regional initiatives • Acknowledge the Integrated Monitoring and Assessment Programme |
| | A healthy and resilient ocean | <ul style="list-style-type: none"> • Set up efficient adaptive/mitigating strategies to react to the accelerated paths of change; carry out test case actions focusing on socio-ecological systems |
| | A productive ocean | <ul style="list-style-type: none"> • Implement test-case studies in the Mediterranean multi-cultural, socio-economic diversified regional setting to develop innovative management strategies based on ‘socio-ecological system’ • Upgrade modelling exercises to improve spatial resolution, and integrate new variables (benefiting of local knowledge, inter alia) to better deal with complex system |
| | A predicted ocean | <ul style="list-style-type: none"> • Enhance observing and predicting capabilities • Set up efficient adaptive/mitigating strategies to react to the accelerated paths of change; carry out test case actions focusing on socio-ecological systems • Build a laboratory for climate change |
| | A safe ocean | <ul style="list-style-type: none"> • Develop impact-based forecasting of marine multi-hazard early warning systems • Improve coastal and deep-sea observational systems |
| | A transparent and accessible ocean | <ul style="list-style-type: none"> • Strengthen the science-policy interface and the flow of knowledge from scientists to the diverse regional policy frameworks • Pursue an open-data approach to ocean data and knowledge • Understand future links with economy and societal needs |
| | An inspiring and engaging ocean | <ul style="list-style-type: none"> • Enhance ‘Mediterranean Sea literacy’ and participatory research • Improve connection and collaboration with existing Mediterranean networks and organizations |
| Capacity development priorities | | <ul style="list-style-type: none"> • Establish North-South and East-West collaboration aligning regional policy frameworks and initiatives • Build structured partnerships to overcome political constraints • Draw up a shared educational strategy for sustainable development |

The Mediterranean Sea is unique in its biodiversity, with 28% of endemic species, and tight inter-connection between marine ecosystems and human activities. About 150 million people are living in the coastal areas, and the basin provides the pathway for 30% of the global sea-borne trade volume (EC, 2015; BlueMed, 2018). Increasing coastal urbanization, human pressures, exerted from marine/maritime activities and climate change are strongly affecting the status of the region. Recent assessments (UNEP/MAP, 2017; UNEP/MAP and Plan Bleu, 2020) showed Mediterranean ecosystems and living resources to be far from Good Environmental Status (GES, COM(2014) 97), as a result of the combinations of the above-mentioned factors.

The last decade has seen the increase of pollution, threatening marine environment, life and health at any level and exacerbating the status of several populations (Casabianca et al., 2020). This became rapidly a critical problem: dead zones, anoxic areas and hot spots of chemical pollution affect ecosystems along with the marine litter (i.e. micro-and nano-plastics and associated Persistent Organic Pollutants (POPs) and Endocrine Disrupting Chemicals (EDCs)) that affects marine environment and organisms mainly through entanglement and ingestion, and colonization and rafting of invasive species or species at risk. Drastically reducing pollution and remediating polluted areas is one of the main transboundary challenges to ensure a "*clean Mediterranean Sea*", increasingly recognizing the existing cumulative threats, including historical, and the need to address them in a coordinated manner, in order to maintain this worldwide heritage as well as livelihoods. The damage and associated social costs of pollution also extend to the economic sectors, such as tourism, aquaculture and fishery, and shipping, and have multiple direct and indirect impacts on human health (review in Landrigan et al., 2020). The nature and magnitude of these effects are only beginning to be understood.

As one of the major stressors affecting the Mediterranean, the fate of pollution needs to be considered in the framework of multiple impacts scenarios driven by climate change and effects of human activities on the marine environment, also in relation with marine hazards. Multiple stressors are also threatening marine biodiversity, with fisheries among the main drivers of

species extinction (e.g., Dulvy et al., 2014). Overfishing has also characterized this Sea and great effort is required to counter this serious problem (FAO, 2020). The on-going transitions in the community composition are modifying marine food webs affecting the most sensitive organisms, playing major roles in the ecosystem functioning and hampering resilience. A "*healthy and resilient Mediterranean Sea*" can be obtained only if marine ecosystems are mapped, monitored, and protected, and the multiple impacts, including climate change, are measured and reduced, in a way that the provision of ecosystem services are maintained. We are now at a crossroads where the relationship between the ocean and world population urgently needs to move towards mutual aid. As it will be explored in the following, citizen-science initiatives and Ocean Literacy have a key role to play in building and sustaining such relationships.

Enhancing the ocean observing capacity, measuring the Essential Ocean Variables (EOVs, www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114) and understanding the complexity of the system to develop sound models and address evidence-based solutions is the key to build a wealthy and safe Mediterranean area. The renowned expertise of Mediterranean scientific community in operational oceanography and forecasting (Tintorè et al., 2019; Le Traon et al., 2019) represents a remarkable strength to build on for future development of the in situ and satellite observing systems and modelling exercises to improve spatial and temporal resolution, and integrate new variables (benefiting of local knowledge, inter alia, and technological developments) and scale-up so as to better deal with complex systems. The knowledge of the sea floor morphology is nowadays also increasingly achievable both in shallow and deep-water environments. In fact, in the last decade seafloor mapping technique have dramatically improved, allowing centimetric resolution and therefore quantitative definition also of the impact of erosional events and definition of the impact of human activities (Madrcardo et al., 2019; Fassoni-Andrade et al., 2021). Such knowledge is the basis also for attempting a broadening of the citizen-science approach by bringing to the public observations that are beyond the normal, direct, and inevitably anthropocentric, view of the environment.

However, it is worth noting that the Mediterranean Sea is still neither adequately observed nor fully understood in terms of early warning observations and forecasting of the impacts of climate change and anthropogenic stressors, from the deep and open sea frontiers to the coastal areas (Melaku Canu et al. 2010; Zunino et al. 2021). Hence, the capacity is limited to understand current and future Mediterranean conditions, project their change and impact on human wellbeing and livelihoods. To tackle the formidable challenge presented by the need to observe, assess and predict coastal seas and nearshore marine ecosystems, first of all existing data gaps and lack of infrastructures in some parts of the basin need to be reduced and measurements of the biological essential variables extended. The superposition of a variety of coexisting inputs and pressures on coastal and nearshore areas can alter the ecosystems. Moreover, the interplay of many physical, chemical and biological processes acting on a wide range of spatial and temporal scales add extra complexity to an already complex picture. Factors such as river inputs, spatial anisotropy induced by the coast, benthic-pelagic coupling, inputs related to terrestrial-based economic

activities are essential components in coastal areas. These are also characterised by very dynamic processes yielding a high variability in space and time, directly influenced by diurnal and seasonal changes, and with additional factors to be accounted for when compared to the open ocean. Coastal marine areas are the focus of the interaction with the land, on one side, and the forcing by the broader shelf water body on the open-sea, and are the most prolific with activities by users extracting services that are crucial for several marine economic undertakings. Improving our ability to predict ecosystem responses to anthropogenic forcing and to move toward a “*predicted Mediterranean Sea*” is a key priority in identifying pathways, policies and actions for monitoring, regulation, surveillance, defence, hazard assessment and alert, and many other needs that often require regular and timely support from coastal observation and forecasting systems.

The key marine hazards requiring a focus to achieve a “*safe Mediterranean Sea*” are, among others: storm surges, tsunamis, harmful algal blooms (HABs), and coastal erosion (Figure 1). Storm surges represent a recurring risk for the population living along

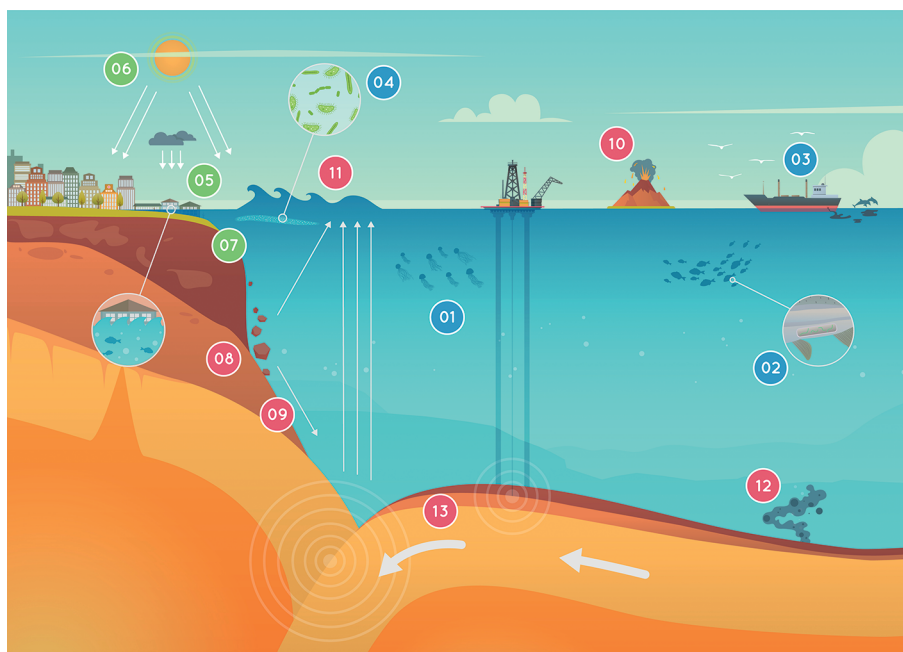


Figure 1. Infographic illustrating the main Biological Hazards (01-Jellyfish proliferation; 02-Impact of parasites; 03-Impact of oil spills; 04-Harmful algal blooms), Extreme Climate Events (05-Storms and surges; 06-Heat waves; 07-Coastal erosion) and Geological Hazards (08-Landslides and slope Instability; 09-Submarine erosion; 10-Volcanism; 11-Tsunami; 12-Destabilization of gas; 13-Induced and natural earthquakes) investigated at CSIC, Spain. (Design Investid Plus. From: Sallarés et al. (in press) From a safer Ocean: towards marine hazard impact mitigation. Libro Blanco CSIC).

the coasts all over the world (Androulidakis et al, 2015). Major tsunamis are relatively low-probability occurrence phenomena which may have very high-consequences and can be triggered by seismic, volcanic, landslides and meteorological sources. In the Mediterranean region, the risk associated with both storm surges and tsunamis is enhanced because its population is concentrated near the coasts. A risk source is also represented by HABs hampering aquaculture activities, seafood safety, marine life and key economic activities for the area such as recreation and tourism, a sector that represents, with few hundreds of millions of tourists every year (except for the pandemic year), more than 90% of the annual economic value of the area, counting connected activities (Randone et al., 2017).

The relevance of a better understanding of risk drivers, risk assessment and reduction in a multi-hazard framework is even more urgent in the incumbent threat of climate change. According to increasing evidence (e.g., <https://ocean.si.edu/through-time/ancient-seas/sea-level-rise>), the projected sea level rise in the Mediterranean Sea may exceed 1 m by year of 2100, thus potentially increasing the risk related to erosion, flooding and salinification of low-lying coasts in the absence of major additional adaptation

efforts. In fact, coastal flooding, erosion and tsunamis, enhanced by sea-level rise, pose at risk several UNESCO World Heritage Sites (WHS) characterizing the Mediterranean region. By 2100, flood risk may increase by 50% and erosion risk by 13% across the region, with considerably higher increases at individual WHS (Reimann et al., 2018).

Marine hazards in the Mediterranean region lead to an ever-increasing risk because more and more assets and people are getting exposed (Figure 2).

A conservative value of the Mediterranean Sea economic assets is in the order of US\$ 5.6 trillion, generating an annual economic value of US\$ 450 billion (Randone et al., 2017). Nowadays, society depends on the ocean more than at any time before.

Ensuring a “sustainable (harvested and) productive Mediterranean Sea” depends on the development of a sustainable management of ocean and coastal resources and on the integration of marine spatial planning with coastal management as key tools to support informed decision making. Despite the recognition of the potential of established, emerging and innovative sectors of the blue economy to bring opportunities for investment for the future development of coastal communities (EC, 2020), effective exploitation of available tools, including information

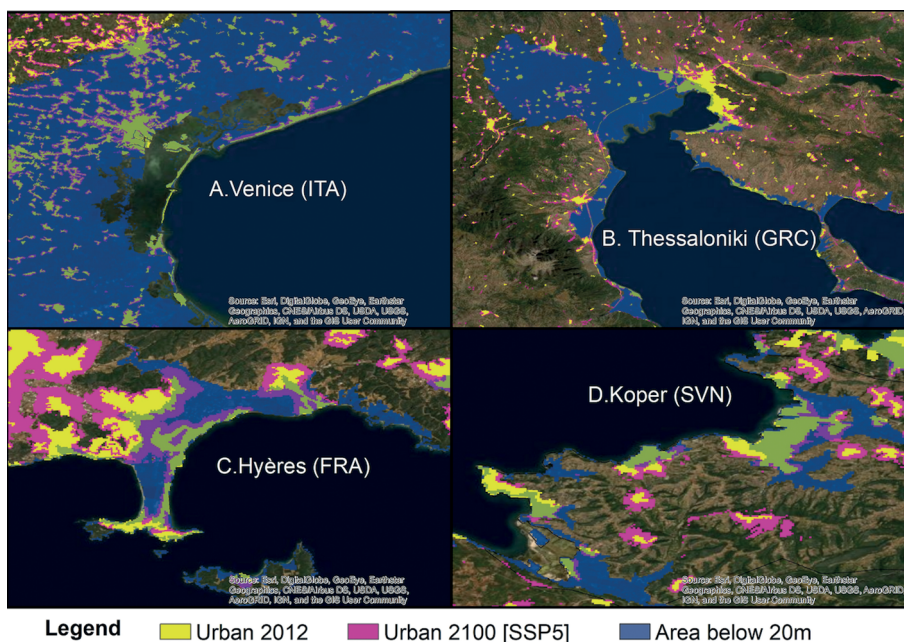


Figure 2. Examples of potential urban development in four selected coastal regions as modelled by Wolff et al. (2020). In dark blue, the area that lies below 20 m is indicated.

and communications technology (ICT), to support decision makers and stakeholders in decoding the complexity of the system and integration of ocean science with social and economic science is still lacking. Science-based safe and sustainable thresholds for economic operations in the Mediterranean Sea need to be defined in order to drive the sustainable exploitation of non-renewable resources and the resources based on the Mediterranean Sea natural and cultural heritage while preserving the environment. Sustainable food production, tackling biodiversity and resources, need to be implemented and the links and mutual feedback between tourism and the environment in the perspective of the circular and inclusive blue economy reinforced.

In this context, integrating data represents an unavoidable tool for assessing the status of marine systems and societies in all of the most urgent issues like biodiversity loss, pollution, healthy seafood products and its fundamental interaction with climate change phenomena (Tunesi et al., 2013; Canonico et al., 2019; Sloyan et al., 2019) as well as with key social and economic activities. To be fit-for-purpose and in the view of a “*transparent & accessible Mediterranean Sea*”, data needs to be processed in a workflow made of many steps: collection, validation, aggregation, elaboration, and so on. Such steps are usually carried out by different bodies and/or authorities using different spatial and temporal scales, but they constitute, as a whole, the foundation to build up the marine data value chain which will serve the data services and users. Long-term archiving is also crucial as monitoring data are used to assess trends, validate and calibrate models, and even when they are considered inaccurate, they represent a benchmark for the definition of accuracy.

Furthermore, ensuring the complete openness of scientific knowledge will allow understanding the future links with economy and societal needs, the formulation of environmental policy and management plans, unlocking ideas and innovation, through a participatory process that is timely and encompasses diversity of interdisciplinary research and interaction with non-academic representatives. According to Shepherd (2018) “to provide a more integrated approach to marine data, allowing the user to search for, visualize, and retrieve in a common way all measurements with one single command wherever the data are stored, the EU embarked upon the construction of a European Marine Observation and Data Network

(EMODnet). To maximise innovation and minimise bureaucracy, marine data should be free of charge and free of restrictions on use”.

Continuous engagement across the diversity of stakeholders, societal actors, and economic sectors is the key to pursue sustainable management of the human activities in the ocean. While Ocean Literacy has been recognized as a key enabler of virtuous engagement, and relevant initiatives have been built targeting the Mediterranean, a consistent effort should be devoted to connecting experiences, exchanging practices, and supporting collaboration among the actors working on science communication and outreach, harmonized among the riparian countries. In this way, reaching an “*inspiring and engaging Mediterranean Sea*” will become possible. As enabler, Ocean Literacy is required not only for bringing science to society and its many actors and sectors but also for inspiring science in delivering fit-for-purpose solutions for sustainable development, bridging the gaps between the ocean science stakeholders, users, and funders in various economic and cultural sectors. It is thus an imperative in establishing science–policy and public–private interfaces (Mackenzie et al., 2019), helping the actors to share the common understanding of basic concepts and facts about the ocean, by developing common narratives as well as common values and personal and emotional connections with the ocean (EU, 2020). Ocean Literacy is also an important contributor to integrating traditional knowledge in the knowledge-generation and sharing process.

In the Mediterranean, it can particularly help narrowing the North-South gap, including in education and science and technology capacities, by favouring knowledge exchange and co-design.

Taking the state of the art into consideration, this White Paper includes the set of trends (section 2), capacity development needs, specific challenges (section 3), and recommendations (section 4) for each Decade’s societal outcome, including cross-cutting issues. The synthesis of these findings as well as of the consultation process is finally reflected in the proposal of a Mediterranean Sea community contribution to the Decade (section 5).

CURRENT STATUS AND TRENDS

This section presents a snapshot of the key issues faced by Mediterranean Sea for each Decade’s

outcome. Preliminary and macro insights on actions to be undertaken can be also derived, projecting into the gaps and challenges.

A CLEAN MEDITERRANEAN SEA

As we saw in the previous section, the Mediterranean basin is threatened by multiple stressors associated with the rapid expansion of coastal populations, urbanization, changes in agricultural, industrial and shipping patterns, overfishing and exploration and extraction of offshore minerals and hydrocarbons (Danovaro et al., 2020; Sprovieri et al., 2020; Sprovieri et al., 2021; Melaku Canu et al., 2015). In addition, 30% of the world maritime traffic is passing by the basin, being the first tourist destination of the world. Also, the basin buffers inland pollution, including significant riverine inputs because of large rivers (Po, Nile, etc.).

Different aspects can be considered as the main causes of marine pollution. The UNEP/MAP Quality Status Report (UNEP/MAP, 2017) highlighted the chemical contamination of sediments and biota, eutrophication and marine litter as the major issues requiring coordinated policy and urgent management responses in order to stem the tide of degradation of the Mediterranean ecosystems. These pollutants enter the Mediterranean Sea as land-based sources either via discharge points and dumping grounds (point source pollution) or from surface fluvial runoff (nonpoint source pollution). Pollutants also enter the marine and coastal environment through atmospheric deposition or due to marine activities such as shipping, mining, and oil and gas exploration. Although land-based sources are dominant in generating marine litter, sea-based sources actively contribute to the problem for some parts of the basin, reaching even 80% in Malta (Liubartseva et al., 2019).

The main types of chronic pollutants in the Mediterranean are oxygen-depleting substances, heavy metals, POPs, hydrocarbons, nutrients introduced by human activities and plastic (Figure 3). While a decrease of general chemical contamination and oil spills accidents have been described, there are still some point sources of priority, emergent contaminants and new contamination schemes (ship emissions, acidification, tourism, etc.).

Offshore waters of the Mediterranean Sea are characterized as oligotrophic, but the highly

populated coastal zone and the riverine input induce eutrophic trends in coastal areas (Sammartino et al., 2015). The main coastal areas in the Mediterranean which are historically known to be affected by eutrophication are the Gulf of Lion, the Gulf of Gabès, the Adriatic Sea, the North Aegean Sea and the South-East Mediterranean (Colella et al., 2016). The assessment most often show that these areas do not reach GES (UNEP/MAP, 2017). Using satellite and model data from the European Commission's Copernicus Marine Environment and Monitoring Service (CMEMS, www.marine.copernicus.eu), UNEP MAP (2017) reported an overall increasing trend of chlorophyll concentration in the Mediterranean Sea over the past twenty years, and a clear increase in the western part of the basin. Criteria for reference conditions for key nutrients in the water column should be harmonized throughout the region.

As regards chemical pollution, the main activities contributing to the emissions are wastewater treatment plants, metal production, pulp and paper production, the chemical industry, and other activities (dyeing of textiles, tanning, ship building, painting or paint removal). Interestingly, the trends and levels of pollutants have generally decreased significantly in the most impacted areas in the Mediterranean Sea after the implementation of environmental measures (UNEP/MAP and Plan Bleu, 2020).

However, several point and diffuse pollution sources are still releasing both priority and emerging chemical contaminants into the Mediterranean. Measures and actions should thus focus on hotspots associated with urban and industrial areas along the coasts (UNEP/MAP, 2017). Regrettably, the intervention scenario is complicated by the lack of data. Limited data availability with insufficient geographical coverage and quality assurance to allow for proper regional assessment, and mostly non-detected concentrations, is shown on petroleum hydrocarbons and POPs from the national coastal monitoring networks.

While levels of heavy metals (cadmium, mercury, lead) in coastal waters, assessed from bivalves and fish against Environmental Assessment Criteria, show a more-or-less acceptable environmental status, concerns regard the coastal sediment compartment for lead and total mercury, indicating an impact from these chemicals, including in foodstuff for lead.

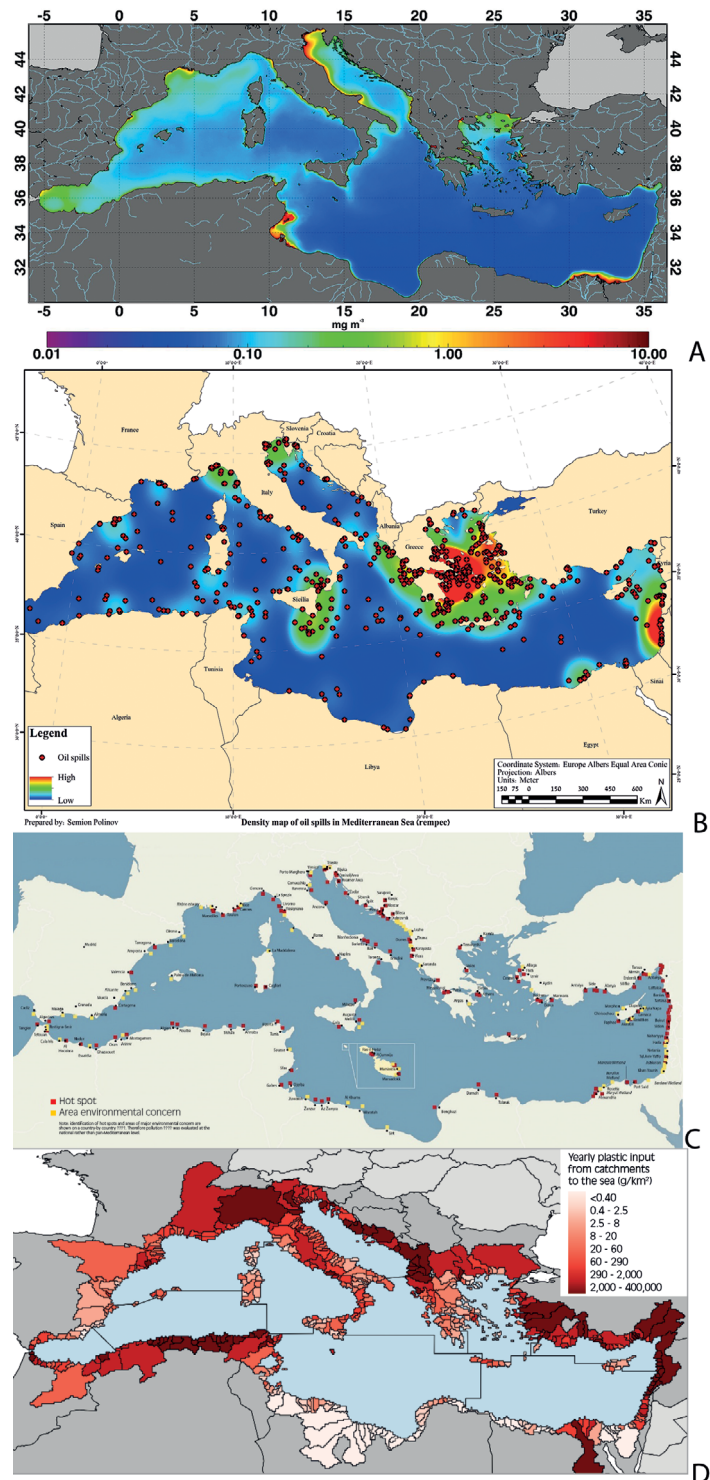


Figure 3. An overview of the main pollution issues in the Mediterranean Sea. A: Chlorophyll (eutrophication, Colella et al, 2016); B: Oil spills (1977-2017, Rempoc databases); C: Major hot spots of pollutions (UNEP/MAP and Plan Bleu, 2020); D: Modelled inputs of plastic pollution (UNEP/MAP and Plan Bleu, 2020).

Emerging pollutants refers to a heterogeneous set of thousands of molecules whose presence in the environment has been detected only recently. This category includes personal care products (antiseptics, sun lotions, cosmetics, etc.), flame retardants, additives, plasticizers such as phthalates, nanoparticles used in food, medicine, construction and textiles, plant-derived substances, perfluorocarbons, pharmaceuticals antibiotics, and non-halogenated substances. These substances can be toxic for marine organisms and humans, if not removed from waste waters. The study of their interactions with the environment and human health and their treatment is extremely complex and is largely insufficient for a number of substances. Although wastewater treatment is improving to eliminate certain substances, we are far, in the Mediterranean Sea, from phasing existing substances out, also due to lack of regulation on the emergence of new substances.

The Mediterranean Sea, representing 1% of the global oceanic waters, is also one of the world areas most highly affected by marine litter due to an increase in plastic use, the lack of recycling, unsustainable consumption patterns, inadequate waste management, high pressures from tourism and shipping, coupled with significant riverine inputs. Inputs of plastics into the sea, as estimated in 2015, are at the level of over hundreds of tons per day (UNEP/MAP, 2015), depending on the coastal population,

which may vary from country to country, representing more than 2% of the total inputs in the world's oceans. Plastics account for up to 95 to 100% of total floating marine litter and more than 50% of seabed marine litter. The Mediterranean is especially affected by microplastics, with concentrations at the sea surface largely above 100,000 items per km² and maxima above 64 million floating particles per km². These concentrations are projected to further increase in years to come.

In the majority of Mediterranean countries, the root causes of pollution are found in ineffective/inefficient waste and wastewater management, in limited regulations, unsustainable consumption patterns, in the increase of plastic use, and possible illegal practices (Figure 4).

In some areas, up to 58% of the municipal solid waste collected is still disposed in open dump sites (UNEP/MAP and Plan Bleu, 2020), and less than one third is recycled, while plastics recycling is less than 6% (WWF, 2019).

Land-use nutrient input is expected to increase, although the many regional and national efforts to mitigate their impact on the ocean and ecosystem. A decrease of plastic wastes remains a challenge and point sources of chemical pollution still exist.

Transitioning to a sustainable and clean economy will require urgent and profound changes in both production and consumption patterns, being the

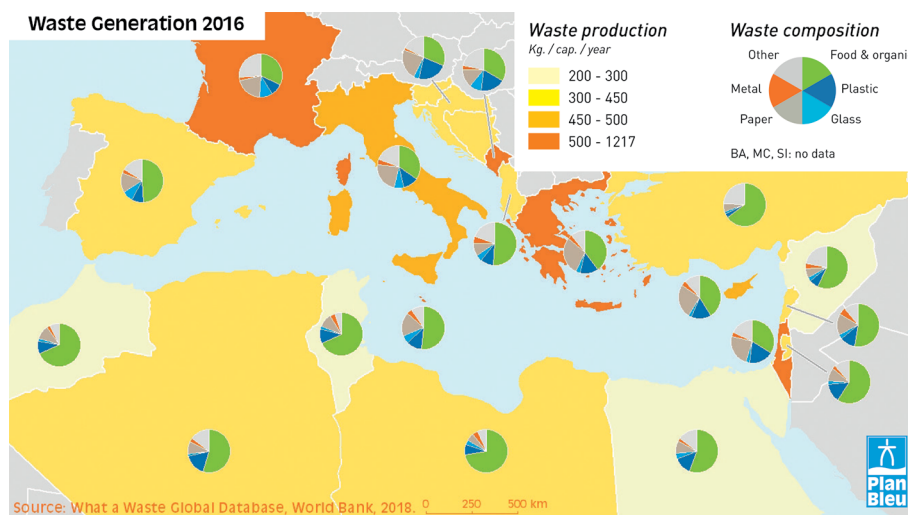


Figure 4. Waste generation and composition in Mediterranean countries, 2016 (Source: What A Waste Global Database, <http://datatopics.worldbank.org/what-a-waste/>).

Single-use plastics product EU Directive (2019) entered into force in July 2021 a strong signal in this regard.

A HEALTHY AND RESILIENT MEDITERRANEAN SEA

The multitude of stressors affecting the ocean caused a great acceleration of marine ecosystem degradation during the last five decades. This applies also to the Mediterranean Sea, a highly variable ecosystem in terms of hydrological and biodiversity changes. To maintain the provision of goods and services, marine ecosystems need to be mapped, monitored, and protected, and the multiple impacts, including climate change, measured and reduced.

For the European Member States of the Mediterranean Sea, the Marine Strategy Framework Directive (MSFD) - i.e., the first European Union (EU) legislative instrument to protect marine biodiversity as the cornerstone for achieving GES - drives the ecosystem assessment. At pan-Mediterranean level, in 2008, the Contracting Parties to the Barcelona Convention decided through their COP 15 Decision IG.17/6 (UNEP(DEPI)/MED, 2008) to progressively apply the Ecosystem Approach (EcAp) to the management of human activities that may affect the Mediterranean marine and coastal environment for the promotion of sustainable development. Both EcAp and MSFD define indicators suitable to capture the status of marine ecosystems based on information originated from monitoring efforts, as to inform policy about this status, drive marine protection in support of marine-related economic and social activities.

The European Commission's 2012 Green Paper (EC, 2012) set out a vision for easily accessible, interoperable and free of restrictions on use digital seabed map of European waters covering topography, geology, habitats and ecosystems, accompanied by timely observations and information on the present and past physical, chemical, and biological state of the overlying water column, and associated data on human activities. As part of its Marine Knowledge 2020 strategy, the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE) launched the European Marine Observation and Data Network (EMODnet, <https://emodnet.eu/en>) initiative undertaken by partnership of over a hundred and fifty organizations working together to assemble

marine data from diverse sources and resources and build gateways to national, regional or thematic repositories, essential contribution to the data and information sharing provisions in the MSFD and the Maritime Spatial Planning (MSP) Directive (Martín Míguez et al., 2019). For example, the EMODnet Chemistry portal for marine data is currently compiling at the European scale monitoring and research data on beach litter abundance, project data on benthic litter and microliter floating data (www.emodnet-chemistry.eu/marinelitter) extensively used to set assessment values for the MSFD Descriptor 10 on 'Marine Litter' (Molina Jack et al., 2019). EMODnet helps ensure the integrity of in-situ data used by the Copernicus program. Data from both EMODnet and Copernicus are distributed according to INSPIRE protocols (<https://inspire.ec.europa.eu/metadata-codelist/ProtocolValue/>) and are thus interoperable.

As far as concerns protection strategies, Marine Protected Areas (MPAs) set on coastal, shallow (24.68%: 0-15 m depth) sites, organized in networks of connected MPAs (Boero et al., 2016) are considered to be playing in the future a central role in the recovery of declining species, habitats and ecosystems (Davidson and Dulvy, 2017). They could support inclusive economics, such as small-scale fisheries (SSF) and ecotourism (Ban et al., 2019), as well as play as "sentinel" sites to observe and counteract climate change, especially in blue carbon ecosystems (e.g., *Posidonia* meadows, Kaal et al., 2019). Nevertheless, a mere 8.9% of the Mediterranean surface is presently under a protection status (UNEP/MAP and Plan Bleu 2020).

Ecosystem modelling has proven to be a suitable instrument to integrate information from monitoring, assess and drive protection strategies (Solidoro et al., 2009). A robust scientific and technological capacity is available to pursue a more advanced monitoring of the Mediterranean Sea: e.g., CMEMS, coastal modelling, and pollution modelling. This 'already-built' capacity can tackle multiple challenges and contribute to solutions, such as supporting a better assessment of climate change effects. In this context, the Copernicus Marine Service is an observation platform that tightly interconnects the same international scientific networks that support and exploit it (e.g., Mediterranean Operational Network for the Global Ocean Observing System - MONGOOS, European Global Ocean Observing System - EuroGOOS, Expert

Team on Marine Environmental Emergency Response - ETMEER).

To obtain a healthy and resilient Mediterranean, it is necessary to promote integration between ecosystem conservation (protection), generation of knowledge of the physical, biogeochemical and biodiversity dynamics on appropriate time scales (monitoring), understanding the effect of long-term cumulative stressors to define the basin vulnerability (assessment), and displaying suitable predictive tools (modelling). Increasing our knowledge about organismal plasticity and response capability, in particular for ecosystem engineer species, is also mandatory, as well as promoting ecosystem restoration. Crucial to the aim is the recognition of long-term impact of humans, starting well before the industrial revolution with repeated episodes of forest clearance and radical change in land use (since the Roman Empire) accompanied by modifications including of the hydrological network through river diversions leading to radically modified coastal and deltaic areas (Maselli and Trincardi, 2013) with substantial impact on coastal ecosystems.

A PREDICTED MEDITERRANEAN SEA

Better prediction of responses, feedback and warning to cumulative human impact and multiple stressors and hazards, and a better understanding of the Mediterranean ecosystem functioning and health, is the basis for its management and adaptation.

In the last 30 years, the scientific community working in the Mediterranean region has cooperated

within a thorough EU strategic planning contributing to the development of regional observing and forecasting systems, which up-to-date evolved to the most advanced research infrastructures and instruments at global and European scale, including CMEMS, thematic clusters of EMODnet, SeaDatNet (www.seadatanet.org/), Joint European Research Infrastructure of Coastal Observatories (JERICO RI, www.jerico-ri.eu/), International Center for Advanced Studies on River - Delta - Sea Systems (DANUBIUS-RI, www.danubius-ri.eu/), European Plate Observing System (EPOS-ERIC, www.epos-eu.org/epos-eric), European Multidisciplinary Seafloor and water-column Observatory (EMSO-ERIC, www.emso-eu.org), European Contribution to the Argo programme (Euro-Argo ERIC, www.euro-argo.eu), Integrated Carbon Observation System (ICOS RI, www.icos-cp.eu/) and Long-Term Ecosystem Research Network (LTER, www.lter-europe.net/lter-europe).

The MONGOOS data center (www.mongoos.eu/) data-center offers a catalog of data from monitoring platforms deployed in the basin. It constitutes a comprehensive catalog of oceanographic measurements available in the region from coastal and open ocean in-situ platforms, High Frequency (HF) radars, profilers and drifters, and gliders, with 47 members from 14 Mediterranean countries providing information of the sea state in near real-time and an updated state of the art of monitoring systems since 2012. Operational modelling systems (Figure 5) developed by MONGOOS members are described in Capet et al. 2020. Access to real-time data from

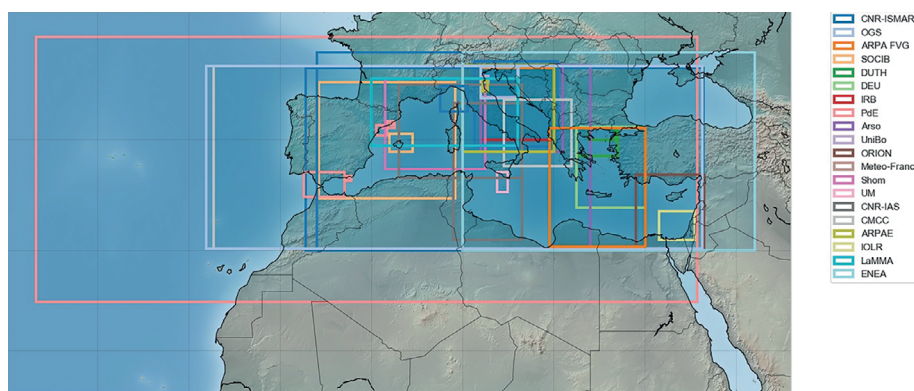


Figure 5. Map of the operational modeling domain of the Mediterranean Sea (Capet et al., 2020).

most MONGOOS monitoring platforms is provided through the CMEMS In Situ Thematic Centre (TAC) and the EMODnet Physics Portal (Tintorè et al., 2019). Deep Sea Observatories equipped with multiple sensors, placed along the water column and on the seafloor are present in the Mediterranean Sea. They constantly measure different biogeochemical and physical parameters that address natural hazards, climate change and marine ecosystems and are part of the EMSO ERIC. A big effort was also made to collect and make accessible historical in situ measurements acquired by the science community during ship cruises carried out in the Mediterranean in the last century. These data, hosted by SeaDataNet and/or EMODnet thematic portals for bathymetry, geology, seabed habitats, chemistry, biology, physics, and human activities are particularly relevant for the fulfillment of the Sustainable Development Goals (SDGs). Despite these efforts, gaps in observation on Central-Eastern Mediterranean and on the Northern African coasts still exist.

Since the early 90's, space-based observations played a crucial role in the development of the Mediterranean Sea observing system (Minnett et al., 2019) highlighting the importance of the development of regional satellite products in order to retrieve more accurate biogeochemical products (Volpe et al. 2012; Organelli et al., 2016; Organelli et al., 2017). Mediterranean regional satellite products are regularly updated and made available by CMEMS Satellite TACs. The new frontiers will be to increase the spatial and temporal resolution of the satellite products, improve their quality especially in coastal areas and to enlarge the number of biogeochemical variables monitored from space.

In the last three decades, several observation-forecasting integrated systems have been established in the Mediterranean Sea to support the implementation of environmental quality targets and objectives, such as the CMEMS and several other local (national) systems. They provide periodic updates on the state of the Mediterranean basin (Tintorè et al., 2019; Le Traon et al., 2019), as well as outlooks, forecasts, projections, and product delivery (von Shuckman et al., 2020) of the main EOVS. The whole chain of integration, sharing and downstreaming of the information at the basin scale and at the local level, has been improved in the last years, also thanks to a number of

Copernicus service evolution projects. However, assimilated models and products are limited to physics and to a few main biogeochemical variables (Salon et al., 2018). According to Capet et al. (2020), 70% of the operational and preoperational products developed in the Mediterranean Sea targets the processes driven by the physical oceanography, such as marine safety, oil spill, sea level monitoring, storm surge, and only 10% of them address water quality, 6%, hypoxia, and the minority of them devotes to other services focusing on the biological components, such as invasive species and living marine resources. Moreover, the specificities of coastal seas are poorly represented.

Improved understanding of the present and future conditions in the Mediterranean Sea is a prerequisite to the development of sustainable ocean economic policies and ecosystem-based management. Such information is needed within or beyond national jurisdictions, servicing and connecting nations and citizens.

While a substantial work has already been undertaken in past decades in this direction, including:

- understanding of the basin-scale, mesoscale, and sub-mesoscales circulation and water masses generation and propagation at different time-scales: from Seasonal-to-Decadal Climate Forecasting;
- analysis and research on ecosystem state and ecosystem functioning;
- using the opportunity offered by European research infrastructure and major programs, such as CMEMS, SeaDataNet, EMODnet, to setting up a Mediterranean integrated and observing and modeling system based on distributed centers that gradually has been transitioned to operation and now is fully operational and therefore can support the development of blue economy products;
- setting up networks of observational platforms and national forecasting systems linked with the regional system;
- develop together with intermediate users prototype tools and/or downstream systems to demonstrate how the system can respond to user's needs down to societal benefit, as for example the observation and modelling tools developed to mitigate the risks and impacts associated with oil spill designed with the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC).

There is still much to do to support sustainable management trends through observations. For

instance, to assess the impact of blue economy developments on the marine environment, the adequacy of the monitoring capacity needs to be constantly assessed, and adapted taking into account users' needs, coping with fast changing monitoring protocols, tools and associated parameters, evolving under the combined effect of new technological developments (AUV, drones, sensors...) and rising societal needs. A first example of this type of assessment was carried out in the framework of the MedSea Checkpoint project (<https://emodnet.eu/en/checkpoint/medsea>, Pinardi et al., 2017) demonstrating the importance of a continuous evaluation of the system and products capability to respond to policy and economy user's needs.

A SAFE MEDITERRANEAN SEA

Storm surges in the Mediterranean region are a relatively common phenomenon, impacting natural environments, damaging infrastructures and affecting economical assets. Coastal floodings develop seasonally, reflecting a combination of astronomical (tides) and meteorological (storm surges) forcing whose impacts can be exacerbated in areas of natural or anthropogenic subsidence (Trincardi et al., 2016). The vulnerability to flooding is therefore in large part the consequence of human uses of the coastal region, including historical diversion of rivers, modification of coastal morphology (including excavation of artificial inlets) and pumping of fluids (freshwater and, in some areas, hydrocarbons) from beneath the coastal areas resulting in high rates of coastal subsidence (Herrera-García et al., 2021). Climate projections and analyses of tide gauge data show different trends in frequency, magnitude and duration of the extreme sea level events in the region, often associated to the rise in the relative mean sea level (Androulidakis et al., 2015; Galassi and Spada, 2014; Lionello et al., 2012; Marcos et al., 2015). The available observational records are too short for assessing multidecadal trends, with the exception of the Northern Adriatic Sea, where an increase in the number of storms is reported (Pomaro et al., 2017). The projected trends have a direct impact to expose the Mediterranean societies to more frequent coastal flooding and subsequent losses. In this respect, studies on trends, variability and frequency of local extremes and the main forcing mechanisms that can induce surges in the

Mediterranean region already detect changes in the duration and spatial coverage of the storm surges associated with a shift in the location of storm tracks, as in the major sequence of flood events that hit Venice in November 2019 (Cavaleri et al., 2020). The analysis of the distribution of large storm surges events and wave activity, especially along the coast, is essential for a complete evaluation of coastal risks assessment and management.

Tsunamis are often classified as a low-probability high-consequences natural hazard. Their impact may reach far beyond their source region. This likely happened for the 365 Common Era (CE) Crete event, which caused widespread destruction. Tsunami impact may be combined with the seismic shaking, like in the case of the 1908 Messina and Reggio Calabria event; it may also trigger cascade effects such as the so-called NaTech (Natural hazard triggering Technological disasters) events, like the 2011 Fukushima nuclear accident. Past tsunamis in the Mediterranean Sea are well documented (Maramai et al., 2014). In recent years, several small to moderate tsunamis have occurred in the Mediterranean region. A significant tsunami triggered by an earthquake of magnitude 7.0 (USGS) occurred off Turkey's Aegean coast and north of the Greek island of Samos on 30th October 2020. One person was reported to have drowned in Siğacık (Turkey) during the event. In addition, damage was reported to cars and small vessels that were swept away by the waves in Vathy, Samos. In south Chios Island (Greece), a few boats were crushed on the breakwater (Triantafyllou et al., 2020). These events are a reminder that the Mediterranean region is prone to tsunamis. There is now the unique occasion of exploiting a recent fully probabilistic hazard assessment (Basili et al., 2021) to inform disaster risk reduction actions, such as long-term coastal planning, awareness raising, and evacuation planning in support of the tsunami warning and mitigation system (Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected sea - NEAMTWS, www.ioc-tsunami.org).

In terms of seafood and resource safety, the Mediterranean Sea harbours more than 80 microalgal species that produce potent toxins, which can cause an array of different human syndromes thus hampering aquaculture activities or result in fish and shellfish kills (Zingone et al., 2021; Quero et al., 2015;

Garcés et al., 2003; Garcés et al., 1999). Possible intoxications and other adverse effects on human health and seafood may be kept under control through increased monitoring activities which are in place in several countries. However, an even higher impact on the use of marine resources and tourism derives from other types of HABs, such as seawater discolorations caused by high biomass blooms and mucilages, which pose economic activities and wellbeing at risk in many coastal Mediterranean areas.

Natural hazards are further amplified by coastal erosion, which in Mediterranean countries has been primarily driven by human interference with natural processes, such as depletion of terrestrial sediment supply or coastal protection elements. Notably, the only existing surge barrier in the Mediterranean basin has been installed in Venice (Umgiesser, 2020). Conversely, submerged breakwaters can reduce wave energy and mitigate erosion and are becoming a common practice in the Mediterranean region. At the same time, interconnections between different types of hazards need to be addressed in research, planning and management for adaptation, as exemplified by the DANUBIUS-RI platform designed to support interdisciplinary research on rivers and seas by facilitating monitoring within various aspects of environmental, social and economic sciences.

Greater safety with respect to the ocean hazards may be achieved only through the implementation of science-based risk reduction. A multi-disciplinary approach towards observing, monitoring and modelling is expected to trigger synergies and foster a more effective and sustainable long-term management and development; know-how transfer within the contributing research community and beyond is needed to build-up on past and present relevant Mediterranean initiatives.

A SUSTAINABLY HARVESTED AND PRODUCTIVE MEDITERRANEAN SEA

The Mediterranean blue economy, pivoting the growth of coastal communities and countries, has been characterized in the last years by a constant growth, if not a rush, often affecting the ecosystems' goods and services (e.g., natural capital, landscape, food) on which it is based and from which it is sustained.

For instance, fisheries and aquaculture represent two key sectors for the regional economy with total estimated revenue of US\$ 12 billion, 100,000 operating vessels, including small boats, and 1 million direct and indirect jobs, according to the General Fisheries Commission of the Mediterranean of the Food and Agriculture Organization of the United Nations (FAO). But overexploitation, also due to Illegal Unreported Unregulated (IUU) fisheries, pose the sector at risk. Though 75 percent of assessed stocks remain over-exploited in 2018, management strategies put in place in the last years are showing encouraging results, with a decrease of 13 percentage points in six years and a correspondingly decreasing exploitation ratio (FAO, 2020). Even more encouragingly, Mediterranean countries have set forth their intent towards strengthening fisheries management and governance by the signature of the Medfish4ever declaration (Medfish4ever, 2017).

Strong interactions and cross-feedback among sectors (e.g., fisheries and aquaculture, tourism, transport, energy, food, conservation, cultural heritage) adds further complexity in the Mediterranean area due to the conflicting use of the limited available space. The "Knowledge Catalogue" for Maritime Spatial Planning (Kannen et al., 2016) promotes the connection of existing geoportals, from national to European to international, on environment and human activities, to support the management of maritime space and to feed at EU level the definition of national plans, complying with the Directive on Maritime Spatial Planning (Directive 2014/89/EU).

In perspective, the potential of Mediterranean blue economy is considered high, triggered also by emerging technologies and technologically advanced applications, such as marine renewable energies that despite a still low commercial development will be the key to support the energy transition phase.

The development of a sustainable productive Mediterranean Sea and equitable prosperity of the area (Stuchtey et al., 2020) lies more than ever in understanding the interactions and interdependencies of the environmental conditions and processes, the use of resources and the economy: on one side, the potential impacts from established (e.g., extraction of marine living resources, offshore oil and natural gas, ports warehousing construction of water projects, shipbuilding and repair,

maritime transport, coastal tourism) and growing (renewable energy, blue biotechnology, deep-sea mining, desalination, coastal and environmental protection, defence and security, marine research and education) sectors and pressures on ecosystems and natural resources; on the other side, the potential impacts from environmental changes on the established and emerging maritime industries and their ability to generate growth.

Science-based safe and sustainable thresholds for economic operations in the Mediterranean Sea must drive the sustainable exploitation of renewable and non-renewable resources and the resources based on the Mediterranean Sea natural and cultural heritage, in the framework of effective marine spatial planning and coastal zone management implementation and of the harmonized implementation of regional and sectoral policies on marine and maritime domains.

Despite many countries and regions are now assessing the potential economic value of their resources, also with the support from the European Commission, through specific financing programme, a major limit to guarantee the long-term capacity to sustain such economic activities is represented by the lack of homogeneity and a poorly managed overall use of diverse and numerous resources (Francocci et al., 2019).

A TRANSPARENT AND ACCESSIBLE MEDITERRANEAN SEA

In the last years, with the advent of new technologies, the way in which data have been produced and used has changed. As a consequence, data have become a tradable and valuable good. The new frontier to make data accessible is the development of the data ecosystem. A data ecosystem is a collection of infrastructures, analytics, and applications used to capture and analyse data. The term ecosystem is used because, like real ecosystems, data ecosystems are intended to evolve over time. And this is the case for earth observation data systems, which rather than a new data portal, is intended as a global data ecosystem of existing infrastructures that allows distributed resources to interoperate, and where users have access to any of these resources through the interface of any component.

The European Union invested in policies and infrastructures to make knowledge of the ocean central to environmental and climate policies as well as the blue economy. Its Member States, together with neighbours, have created during the last 20 years an

unrivalled marine data and forecasting infrastructure through the European Research Framework Programmes FP6, FP7 and Horizon 2020, the Marine Knowledge Strategy and Copernicus. Working together, the principles of free and open access, of FAIR (Findable, Accessible, Interoperable, and Reusable) data (Wilkinson et al., 2016), and the “measure once, use many times” principle, largely promoted through, have demonstrated clear value. Adhering to the FAIR principles with free, timely, and unrestricted access to ocean observation data is beneficial for the originators, has obvious benefits for users, and is an essential foundation for the development of new services made possible with big data technologies (Tanhua et al., 2019). SeaDataNet, the pan-European infrastructure for ocean and marine data management, is a unique example of the association of connected data centres collectively working to improve the quality and effectiveness in the management, the processing, and the dissemination of oceanographic data at national, regional and global levels, in line with FAIR principles. The EMODnet with its seven discipline-based thematic portals expanded and extended the partnership to over a hundred and fifty organisations working together to assemble marine data from diverse sources and resources to make them more accessible and more interoperable. EMODnet adopted SeaDataNet tools and services and worked in synergy to adapt the existing data infrastructure to the new data types and technologies. The collaboration of EMODnet is providing a good example of how to build partnerships to fully exploit the marine data value chain and this could contribute to the decade objectives (Martín Míguez et al., 2019). Collaborative working services (Virtual Research Environment) that provide open and free access to data and tools for research will contribute to enhance scientific and educational capabilities getting maximum value from data and, at the same time, to reduce the inequity between northern and southern countries, which is particularly noticeable in the Mediterranean region. The European Commission is providing data and information products and services to monitor our human activities, planet and environment. As far as the ocean is concerned, two Directorates-General of the European Commission, i.e. Defence, Industry and Space (DEFIS) and Maritime Affairs and Fisheries (MARE), are supporting complementary initiatives: the Copernicus

Marine Service and EMODnet that both distribute open access marine data, interoperable and free of charge. DG DEFIS and DG MARE have signed in 2016 and then in 2019 a Memorandum of Understanding to closely collaborate in data management, data validation and product generation. In practice, the Copernicus Marine Service and EMODnet are joining forces at coordination and operational levels to emphasize the complementarity of their respective marine data offerings.

Nevertheless, there are still large omissions in the available data and monitoring gaps at the basin scale. The SeaDataNet database content shows more than 357,000 data sets (see Figure 6) in the Mediterranean Sea from different disciplines and parameters (bathymetry, physics and biogeochemistry), 79% of which are open access (Figure 6A) while 21% are still restricted (Figure 6B). The percentage of unavailable

data is constantly decreasing thanks to the increasing trust for data infrastructures, new European incentives towards Open Science and available tools, like persistent identifier to allow acknowledge scientists as well as institutes thanks to the citation index assigned to the data sets. While technology transfer allows less developed countries to reach equal opportunities and results, shared developments and responsibilities allows raise awareness on common goals. Data policy should consider the variety of data types and sensitivity of information. The percentage of restricted data and their provenance can indeed be continuously monitored through metadata, directly from the web portals. The largest percentages with the respect to the relative amount of shared data are from Tunisia (93%), Morocco (87%), Slovenia (50%), Spain (44%), Turkey (40%), to reach the minimum value of France (3%), which is the country that after

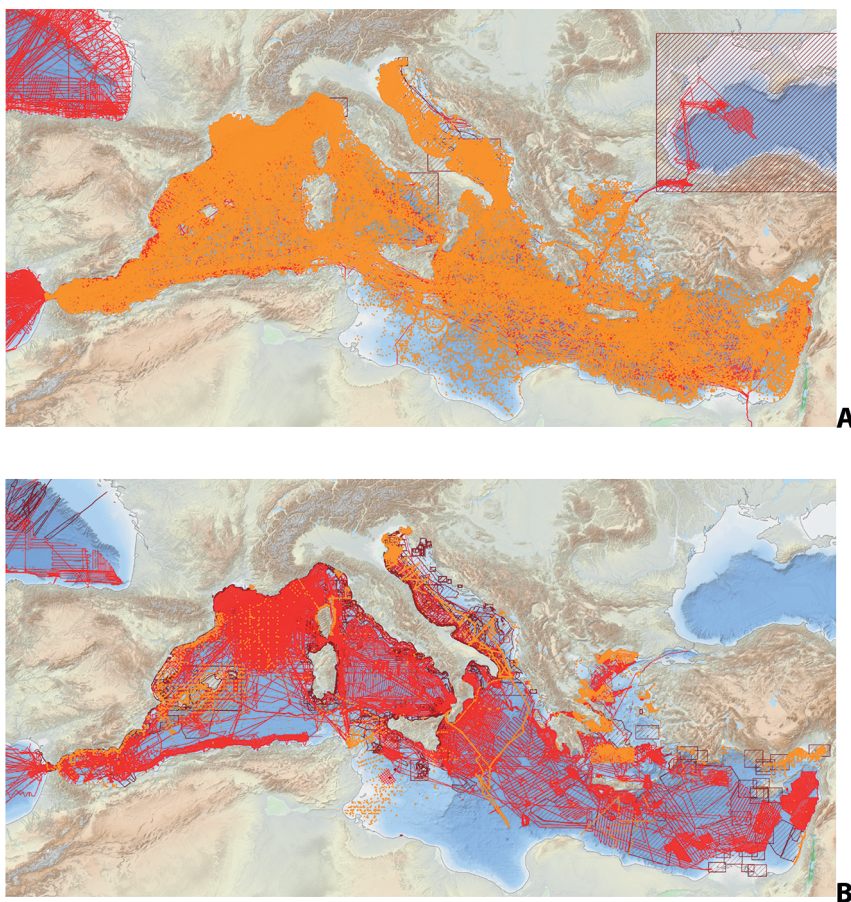


Figure 6. Maps of the open access A and restricted access B data sets available from SeaDataNet data access service (<https://cdi.seadatanet.org/search>).

Italy contributes the most. Another interesting piece of information is that the percentage of restricted temperature and salinity data is still too high among EU countries (i.e. 25% for Italy, 38% for Spain, 11% for Greece) with respect to other parameters even if they are not considered as sensitive ones. The spatial distribution of observations in Figure 6 calls attention to where omissions and gaps locate: along the southern coasts, mainly between Tunisia and Egypt, along Turkish and Croatian coasts and in most of the Sicily Channel.

Both maps and statistics indicate a gap between EU and non-EU countries in monitoring and data sharing capacities that appear as North-South and West-East data distribution differences. This pattern reflects the geopolitical situation of the Mediterranean region and the disparity in access to funding, technology and education in ocean science, which might be faced building trust among the riparian countries and with the EU through multilateral agreements and long-term collaborations on data sharing which include capacity development and appropriate technology transfer in order to be effective. The Global Ocean Science Report (IOC, 2020) provides a baseline for the forthcoming Ocean Decade, assessing the status of the global ocean science economy in the broader context of valuation of ocean spaces (and its uses) and resources.

Blue economy developments on the marine environment and spatial planning requires to have access to information that are rarely collected by the science community. To this end, data from many sea-based sources involving the private sector, which collects a relevant amount of monitoring data on both *ante* and *post-operam* phases, need to be made available as raw data and not only in summary reports, to complement sources, in particular land-based, adequately monitored by public authorities. These data need to be integrated in the present data sharing infrastructures.

This requires new legislation to commit all Mediterranean countries and stakeholders, to cooperate in sharing data and monitoring efforts should be faced at the science-policy interface and bring about a new concerted data policy. Challengingly, the foundation of such a process is political stability needed to guarantee continuity.

Finally, the Ocean Digital Twin (ODT) is now emerging as digital framework, in the broader context of the Earth twin (Bauer et al., 2021) and taking inspiration from the urban intelligence cities' model (Castelli et al., 2019), to continuously collect, analyse and visualise marine information. The integration of vast amount of available oceanographic and biochemical data, modelling and simulation along with high-performing computing (HPC) and Artificial Intelligence (AI) enables to study the ocean as a complex system including the relations among the different components (morphological, geological, chemical, physical, biological, socio-economic of coastal communities). As a tool that 'follows' the real dynamic evolution of the system with increasing accuracy, Digital Twin technology enables users not only to develop knowledge to support interventions and solutions, including preventive actions, but also to explore and understand the consequences towards a dynamic ocean management.

AN INSPIRING AND ENGAGING MEDITERRANEAN SEA

'An inspiring and engaging ocean' refers to Ocean Literacy and societal engagement. Closely interlinked, they are both required for bringing science (its findings or needs) closer to society and its many actors and sectors, and society, its economy and culture - closer to science.

Ocean Literacy provides the needed platform for multi and transdisciplinary collaboration and a common language to build and reinforce relationships, develop capacities, and connect experts, stakeholders, and society around the topics of sustainable development. Intertwined with societal engagement, it has the potential to enrich various sectors of society in solving sustainability challenges and meeting its opportunities as well as to build a legacy of dialogue, understanding, a cross-fertilization. This is particularly important in a region as the Mediterranean where multi-cultural experiences and remarkable North-South unbalances, including education and gender, co-exist.

Recognizing Ocean Literacy as a key enabler of sustainable management of the human activities in the ocean, IOC has built a global Ocean Literacy portal to bring the Ocean Literacy narratives to a wide range of societal actors, from policy to education. At the

regional level, the European Commission's EU4Ocean Coalition (<https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1482>) is being developed as a platform for European citizens, scientific, industry, and education actors to co-develop Ocean Literacy actions. Ocean Literacy is also being addressed by different sectors, from academia to industry, education, and science. Networks like the Consortium for Ocean Science Exploration and Engagement (COSEE) or European Marine Science Education Association (EMSEA) have been fostering Ocean Literacy with an emphasis on education. Industrial organizations and clusters, e.g., TMA BlueTech™, have been promoting the importance of Ocean Literacy for sustainable blue economy and maritime careers. Scientific associations, e.g., EuroGOOS, have been empowering scientists as Ocean Literacy stewards. Art institutions, e.g., TBA21's Ocean Space, have been promoting the mutually enriching and ever-expanding connection between science and art.

In the Mediterranean, activities related to Ocean Literacy, environmental education, and education for sustainable development have been developed and implemented by scientists and educators who have joined forces to adapt the seven essential Ocean Literacy principles to the Mediterranean region. The EMSEA Med-Working Group delivered the "Mediterranean Sea Literacy" (MSL) guide, comprising seven principles and 43 concepts, all adapted to the specificities of the Mediterranean region (Previati et al., 2018; Realdon et al., 2018). The MSL principles and concepts, serving as guidance for educators, teachers, scientists, non-governmental organizations, policymakers, blue economy sectors, and the general public, are expected to raise awareness towards a Mediterranean-Sea-Literate society (Mokos et al., 2020). Ocean Literacy is also a key asset of several regional initiatives, programmes on education and capacity building, e.g., Mediterranean Strategy and Action Plan for Education for Sustainable Development, Mediterranean Education Initiative on Environment and Sustainability (MEdIES), as well as of universities' networks, e.g., Euro-Mediterranean University (EMUNI), Union of Mediterranean Universities (UNIMED), European University of the Seas (SEA-EU).

An important target for the Ocean Literacy in the Mediterranean is the engagement with traditional and local knowledge holders as essential partners in the understanding of phenomena and the definition of solutions to the environmental challenges. An example from fishery research demonstrates how the ecological knowledge of fishers can help track the geographical expansion of both native and exotic fish species (Azzurro et al., 2011; Boughedir et al., 2015) and fill data gaps in the distribution of exotic species (Elbarassi et al., 2014). These types of initiatives will have to be increased and intensified also through marine citizen science activities.

In terms of societal engagement, citizen science represents a promising way to address current ocean knowledge gaps and build capacities for governments and communities to enable conservation action worldwide (Kelly et al., 2020). Participation in marine citizen science actions has proven to enable communities to engage with the ocean and inform themselves (and potentially their wider social networks) on topics such as ocean and climate nexus, marine species redistributions, plastic pollution, and marine environmental planning, among many others. Still, the ability to make it visible, the evolution of spots, such as the sea floor, commonly hidden to non-specialists but increasingly impacted by human activities is insufficient (Pierdomenico et al., 2019; Madricardo et al., 2019).

Community-based citizen science efforts can also enable a more efficient science-society-policy interface. Stakeholders' mobilization, including around the Ocean Decade, has been promoting a better understanding of the Mediterranean environmental issues and the importance of ocean science to find solutions. Ocean-focused education and a sense of personal attachment are integral to the development of marine citizenship (Mckinley and Fletcher, 2010). Bridging the Mediterranean communities together around the topic of Ocean Literacy will contribute to the shared feeling of ocean citizenship and stewardship in the region. To this end, it will be of outmost importance for the numerous organizations and networks working on marine issues in the Mediterranean to develop and coordinate engagement strategies and capacity development programmes to broaden engagement with stakeholders and societal actors in the region.

KEY SCIENCE AND CAPACITY DEVELOPMENT NEEDS: FROM GAPS TO CHALLENGES AND OPPORTUNITIES

The key issues under attention by the Mediterranean science community have been examined in the previous paragraphs in relation with the seven Decade outcomes. While specific science and capacity development gaps and needs can be associated with each of them, new opportunities open-up by meeting them with a cross-cutting approach. Table 2 provides a synoptic overview of the main gaps for the seven Decade outcomes in order to allow an immediate comparison of the interrelation between each of them. The complexity of the issues to be tackled makes it clear that they cannot be addressed by science and technology alone while science-informed governance measures need to be put in place.

In particular, considering its highly polluted status, to secure a *clean Mediterranean Sea*, the specific gaps, reported in Table 2, need to be overcome. Critical research priorities include: describing the cycle of plastic with consideration of specific Mediterranean issues (deficient wastewater treatment plants-WWTs, maritime/fishing sources, etc.); acquiring a more comprehensive set of data in order to assess accurately trends for nutrients/eutrophication; considering point sources of priority, emerging contaminants (land based run-off, atmospheric deposition), and contamination schemes (ship emissions, impact of tourism, etc.). In addition, other pathways of contamination or changes in the environment, which relates to more global problems like acidification, may have regional specificities and patterns to be understood.

The challenge of pollution reduction is also part of future integrated observing and forecasting systems, coupling earth system predicting models and tailored end-user products for societal benefit (Tintoré et al., 2019).

Finally, while relevant frameworks are in place to allow synergistic operations (e.g., the Integrative Methodological Framework (IMF) produced by the Priority Actions Programme Regional Activity Centre (PAP/RAC) of UNEP/MAP, the Intergovernmental Hydrological Programme (IHP) of UNESCO, EC and Global Water Partnership-Mediterranean (GWP-Med)), appropriate governance is still needed, overcoming the lack of adequate and persistent political

commitment, “silo” effects and fragmentation in administrations, overlapping mandates and difficulties in meaningfully transposing international commitments into national and local legislative frameworks and practices.

A better interoperability and integration between existing data and databases (Programme for the Assessment and Control of Marine Pollution in the Mediterranean-MEDPOL, EMODnet, national databases, etc.), and information from scientific work or environmental assessments, would improve the science-to-policy agenda and will enable to tackle the challenge of developing new monitoring indicators, defining thresholds and baseline levels, harmonizing procedures to implement policies and management. Cooperation opportunities are offered at first by the Ocean Decade agenda, which clearly define objectives for marine pollution, including those of SDG14: Life below Water. At regional scale, coordinated actions to assess the state of the environment and reduction measures, such as those by UNEP, add since many years to National Action Plans. Furthermore, regional and EU initiatives such as the BlueMed Pilot Action for a healthy-plastic free Mediterranean Sea, the zero-pollution plan from the “Green Deal”, the Horizon Europe Mission Starfish 2030 (EU, 2020) and relevant European directives, offer opportunities to support actions on the reduction of pollution and monitoring activities of European Member States and neighbours.

The resilience of the Mediterranean Sea cannot be unlimited and will not “buffer” all the threats, since already reacting to the climate change, acidification, extreme events, accidents, overfishing, adding to accumulated pollution. To reach and keep a *healthy and resilient Mediterranean Sea* the following gaps, hinted in Table 2, need to be addressed for protecting, monitoring, assessing and modelling the ecosystem.

- *Ecosystem protection.* Marine Protected Areas (MPAs) are lacking enforcement and effective management, often restricted to shallow coastal areas, and poorly integrated in the wider social and economic environment (e.g., Amengual and Alvarez-Berastegui, 2018; Boero et al., 2016). Furthermore, at the MPA-network level, the main gap is the low ecological representativity and connectivity (Guidetti et al., 2013; Jenkins and Stevens, 2018). Bridging these gaps, beside increasing knowledge on climate change impacts

Table 2. Specific scientific and capacity development gaps for the seven Decade outcomes (grey circle with white cross) and main interrelations for each of them (grey circle).

| | A clean ocean | A healthy and resilient ocean | A predicted ocean | A safe ocean | A productive ocean | A transparent and accessible ocean | A inspiring and engaging ocean |
|--|---------------|-------------------------------|-------------------|--------------|--------------------|------------------------------------|--------------------------------|
| GAPS | | | | | | | |
| Understanding of primary sources and pathways for the transport of pollutants, including the mapping of pollution hot-spots and their impacts on ecosystem and human health, as well as link with social and economic activities. | ⊗ | ● | ● | | ● | | |
| Linking pollutant fluxes with economic sectors, identifying monitoring indicators and implementing the planning/management measures of the entire water cycle for the terrestrial components, based on appropriate science and technology, as well as all available science/policy interaction. | ⊗ | | ● | | ● | | |
| Better understanding of physical/biogeochemical/biodiversity dynamics on climate time scales, adopting a comprehensive ocean observing system (protection/monitoring), improving the quantitative knowledge of ecosystems (assessing/modelling) and their functioning (including organismal response to environmental stressors) as the basis for their management (increasing MPAs level, integrating MSP and ICZM) and adaptation. | | ⊗ | ● | | | | |
| Ensuring systematic observations and continuity of data records in north and south of the Mediterranean and extending the range of observations to include biological and ecological EOVs also in coastal area and including novel observations on marine ecosystems to higher trophic levels, fisheries, genomics, pollutants. | ● | ● | ⊗ | | | ● | |
| Monitoring the coastal-open ocean exchange, mesoscale and sub-mesoscales dynamics on ecosystem functioning and the sea floor morphology in four dimensions in areas characterized by natural (i.e. coastal erosion, deltaic deposition, mass transport) or anthropogenic modification (i.e. infrastructures, dredging). | | ● | ⊗ | ● | | | |
| Adopting numerical models which serve to extrapolate observations in both space and time at the resolution required to understand the coastal and nearshore marine areas and which include marine ecosystem processes and components needed to understand the dynamics of coastal and nearshore marine areas, also nested with open sea models. | | ● | ⊗ | | | | |
| Better understanding of the interactions and interdependencies of the environmental conditions and processes, the use of resources, the economy function and sustainability at the ecosystem level (rather than at the species level) and of the inter-relationships between species. | | | | | ⊗ | | |
| Data availability by exploiting the synergy of in situ and space observation and forecasting to predict Mediterranean coastal areas in support of multi-hazard early warning systems and of modelling the effects of the mutual interaction of various sources of hazards and environmental changes. | | ● | | ⊗ | | ● | |
| Understanding of the seasonal and interannual variations of HABs events and the changes in their intensity and distribution at the local and regional scales. | | | | ⊗ | | ⊗ | |
| Adequate awareness and involvement of decision makers, communities, citizens, teachers, media, to influence behaviors and perceptions of different actors towards effective sea actions (<i>sensu</i> Ocean Literacy). | ● | | | ● | | | ⊗ |

for adaptive management, would promote inclusive and participatory MPA planning and management processes engaging local socio-economic stakeholders such as fishermen and tourism actors, etc.), as well as trigger the methodologies to demonstrate and measure MPA connectivity, at the Mediterranean level.

- *Ecosystem monitoring.* Gaps in the integration of all spatial planning and management measures taken under various policies (Fisheries, MPAs, Agriculture) have to be filled (Qiu and Jones, 2013) by incorporating Integrated Coastal Zone Management (ICZM) and MSP with other initiatives present in the region and enhancing the capacity on national institutions and experts to effectively monitor, detect and predict climate change scenarios and impacts in the marine ecosystems (Capotondi et al., 2019), reaching a deeper knowledge on species tolerance to warming, pollution, biological invasions, with a focus on endemic, keystone and engineering species (e.g., Pazzaglia et al., 2021; Pérez-Portela et al., 2020). Establishing mechanisms to exchange experiences and disseminate knowledge, information, best practices and training on the new products are meant to support the creation of a Mediterranean marine science partnership for a concerted dialogue between the scientific community, the industry and policy makers.

- *Ecosystem assessment.* MSFD provides a framework for implementation of a standardized approach, as quantitative as possible, aimed at a coherent representation of the GES, and the 11 MSFD qualitative descriptors drive EU Member States to identify concrete elements to define GES in practice. The Barcelona Convention EcAp roadmap have also adopted a list of 11 Ecological Objectives, (www.unenvironment.org/unepmap/what-we-do/ecosystem-approach) addressing all key elements of the Mediterranean marine environment, further broken down into Operational Objectives COP 17 Decision IG.20/4 (UNEP(DEPI)/MED, 2012), as well as GES definitions and associated targets (COP 18 Decision IG.21/3 (UNEP(DEPI)/MED, 2013). It is crucial to assess marine biodiversity status by integrating *state descriptors* relating to specific environmental components, such as D1. 'Marine biodiversity', D4. 'Marine trophic network', and D6. 'Integrity of the seabed' (Hay Mele et al. 2020) - and *pressure descriptors* - closely connected to the

status descriptors, such as D3. 'Selective extraction of species' (e.g., Gascuel et al. 2016).

- *Ecosystem modelling.* Increasing the situational awareness of coastal seas at the scale of cities and urban areas will allow targeting the land-sea interface (Todd et al. 2019), by integrating models focusing on the 'river-sea continuum', 'estuary models' (simulating the freshwater release on the sea and the salt intrusion into the land), 'storm-surge' models (coupling hydrology and wave/tidal dynamics) and, under a holistic perspective, 'Lagrangian particle models' suitable for predicting the transport of pollution and sediments originating from land and to study ecological connectivity (Falcini et al 2020).

The gap analysis opens a perspective on the following emerging challenges:

- developing more comprehensive ecosystem models and integrating them with novel observation types, including combined satellite and *in situ* measurements, ocean gliders and Argo floats (Terzic et al., 2019; Chai et al., 2020), animal tracking networks, marine biodiversity observation networks (Moltman et al., 2019), genomic data (Valentini et al., 2016; Fanelli et al., 2020) and more (Benedetti-Cecchi et al., 2018);

- putting into practice lessons learned from the first cycle of application of MSFD (ended on 2020) and expanding the array of relevant, unconsidered descriptors (e.g., Caruso et al., 2016), including the selection of a new generation of early warnings indicators (e.g., Traboni et al., 2018).

- empowering coupled observational and predictive tools, by promoting a downscaling from the global to the regional dimension, as well as enhancing regional mapping of pollution hotspots (oil spill and plastic), as mentioned above, and hazards to drive proactive responses (e.g., translocation of aquaculture plants).

In this framework, establishing mechanisms to exchange experience and disseminate knowledge, information, best practices and training is a not to be missed opportunity meant to support the creation of a Mediterranean marine science partnership for a concerted dialogue between the scientific community, the industry and policy makers, in line with the SDG17: Partnership for the goals.

As reported in section 2, observations on their own are not sufficient, so the development of observing capacity and its sustainability in the long term will represent a major transversal challenge in

the coming years for all countries to fully reach a *predicted Mediterranean Sea*.

To tackle this challenge, the relevant gaps reported in Table 2 need to be addressed at first. A required step forward is the integration of satellite observations with the sparse *in situ* offshore and coastal observations into AI and/or numerical models to bring out the synoptic 4D description of Mediterranean (Sammartino et al., 2020) and its marine coastal areas (Melet et al., 2020). Several scientific challenges still exist related to the need of improving the observing capabilities at small spatial and temporal scales, to capture their variability, to improve model-data integration and uncertainty estimation (Tintoré et al., 2019), and to address the biological and ecological dimensions, which are essential components to meet the society demand.

When these challenges will be fully tackled, the Mediterranean observing and forecasting system will serve to provide augmented observations which integrate direct observations (including satellite data) to numerical models leading to climatological descriptions in the long term, supplying the information needed to identify ocean variability in our coastal seas, provide the basis for the scientific determination of environmental thresholds, and of course ultimately support the marine environmental monitoring efforts with the broader view on the state of the marine environment. Moreover, these systems will support the future climate scenarios analysis at the appropriate scales. Further providing open data services in the local scale according to user needs, such a system will finally serve the knowledge-based society and boost the private sector through value addition and innovative smart data application.

Partnerships should be strengthened between the existing research and technology coordination, infrastructure, and observing networks, among others EuroGOOS, including MONGOOS, Global Ocean Observing System (GOOS), International Oceanographic Data and Information Exchange (IODE), and established and developing Research Infrastructures' Consortia (e.g., at European level EMBRC, LTER, ICOS RI, DANUBIUS-RI, EMSO-ERIC, JERICO RI, EURO-ARGO ERIC). They should connect the Mediterranean to the global met-ocean information infrastructures and protocols as well as support the human capacity development by improving skills,

such as computational skills in high-performance computing (HPC). The Mediterranean basin has the opportunity to be transformed into an international laboratory for integrated observation and predictive capabilities for the assessment of the impacts of climate change and multi-stressors on the ocean ecosystem and its services. Relying on multi-models and ensembles for the analysis of future trends and climate projections, scientific advice can be provided to policymakers to support the development of a sustainable and science-based blue economy, by elaborating and performing model-based scenario analysis to explore the diverse possible outcomes of different political choices. To define safe and sustainable thresholds for economic operations in the ocean will help policymakers and stakeholders reaching a *sustainably harvested and productive Mediterranean Sea* implementing a truly sustainable blue economy. New research should develop and flesh out sustainable blue-green growth agendas and link it to efforts in ecosystem protection.

To fill the specific gaps in Table 2, there is the need to: better qualify and quantify the concept of a "productive Mediterranean Sea" and identify sound and applicable sustainability indicators; prevent unsustainable exploitation of marine biological resources that can be improved by acquiring better knowledge on mesopelagic fauna; develop innovative aquaculture solutions (i.e., Integrated multi-trophic aquaculture-IMTA, offshore, multi-use) and effective early warning systems to manage food security risks; improve public and private partnership to fulfil Environmental Impact Assessment procedures which require monitoring programs to be planned and implemented (Gonzales et al., 2015). The contribution of private companies to environmental data collection, rare in the past, is the key to support prediction and mitigate the climate change impacts on population and blue economy. For example, renewable energy installations are considered to play a major role in order to meet the commitments of Paris agreement on Climate Change. Maritime archeology and cultural heritage also represent an emerging opportunity that involves monitoring data to assess the level of conservation, a chance for fruition and study of the past.

One main priority for the region is the necessity to move from hazard- to impact-based forecasting in order to better quantify and communicate economical and societal impacts of direct and triggered hazards.

For a science-based risk reduction, encompassing uncertainty quantification and management along the entire warning chain is of uttermost importance as well as the improvement of the monitoring capabilities for uncertainty reduction (e.g., Angove et al., 2019), and development of integrated multi-hazard early warning systems within a sustainable infra-structural framework (e.g., All Risk Integrated System TOwards Trans-hoListic Early- enhanced European Natural Hazard Scientific Partnership (ARISTOTLE-eENHSP, <http://aristotle.ingv.it/tiki-index.php>; EPOS-ERIC, EMSO-ERIC).

In a regime of limited planning, optimal planning of the monitoring networks is required. Increasing data availability calls for the construction of a more efficient, cost-effective and reliable data exchange infrastructure, for the full exploitation of the sources of information, while the enhancement of data, data products software and service integration, provision and maintenance shall be implemented once the systematization of existing data sources has been achieved. For this reason, the integration of the existing observatories and the extension of existing networks for the creation of operative off- and onshore real-time monitoring networks is the mandatory starting point to respond to future needs. Following this and even in parallel, the development of innovative methodological approaches and technologies for monitoring (Global Navigation Satellite System-GNSS, Earth Observation, cables and smart cables, automatic buoys, e.g., Howe et al., 2019) can bring integrated effort towards better forecasting and uncertainty reduction. Further integration of approaches and disciplines would also maximise the exploitation of the possibilities offered by AI and HPC tools and resources (e.g., The European High Performance Computing Joint Undertaking - EuroHPC, <https://eurohpc-ju.europa.eu>).

In this respect, the Ocean Digital Twin scenario opens-up a bunch of opportunities. Through new campaigns in the future, the simultaneous use of networks of physical and biochemical sensors (sensors everywhere), satellite systems, intelligently interconnected underwater systems (e.g., IoT and IoA, Internet of Things and Internet of Actions respectively), marine vehicles (ROVs, AUVs, gliders, Argo floats, oceanographic vessels), the amount of data made constantly available will increase dramatically.

This data will also - increasingly - have to be rapidly analysed to become input for operating systems and models or processed in near-real time through everywhere computing during the same measurement campaigns, and immediately integrated with already existing information. This will allow both to extract new knowledge and to direct the growth, in an intelligent and targeted way, of new information through new measurements and monitoring to dynamically influence planning and management processes.

To take advantage of these opportunities, available data infrastructures such as SeaDataNet and EMODnet need to be reinforced in the Mediterranean Sea, and the collaboration with CMEMS and Regional Activity Centre for Information and Communication (INFO/RAC) needs to be strengthened. An ecosystem of existing data systems should be built as a bottom-up effort that, sustaining its network of interconnected data centers, strengthens its foundations. The roles of the data collectors and data providers are increasingly differentiating and specialising. The entire data processing chain (from the origin to the final aggregation on the data infrastructure) integrates and interoperates. In a *transparent and accessible Mediterranean Sea* open data quality need to be always ensured. To implement an overarching process to assure good quality of data (Quality Control/Quality Assurance-QA/QC, provenance, transparency, full metadata description and allowing reassessing and reprocessing capabilities), it is fundamental that the validation process reports back to the data sources that are the main responsible for the “master” copy of the data and are responsible for updating and providing access to its best copy. Closing the validation loop will ensure quality improvement on the long term (Giorgetti et al., 2018).

While increasing data availability opens to new opportunities, specific pre-existing challenges should not be overlooked in the warning chain. For example, despite the upstream component is well in place, early warning for near-field tsunamis characterized by a short lead time as well as for tsunamis of non-seismic origin (landslides, volcanic, meteo-tsunamis) remains problematic. Moreover, the downstream component, that is the “last-mile” of the early warning process, is still far from the final implementation mostly due to the relatively low awareness of the tsunami risk, both of the general population and decision-makers

(e.g., Cerase et al., 2019). The implementation of the “Tsunami Ready” program is indeed a priority for the IOC during the Decade to strengthen the NEAMTWS. This should go along with the risk-informed coastal management (e.g., Tonini et al., 2021).

In the case of hazards of biological nature, such as those related to harmful algal blooms, habitat destruction and biodiversity loss caused by environmental deterioration, the main limitations stem from the lack of biological data and related observation systems for large stretches of coasts of the northern coasts and for the majority of the eastern and southern Mediterranean coastal areas (Garcés E. and J. Camp, 2012). The focus of future actions in this respect is to improve our understanding of HABs and of the biological mechanisms underlying them through targeted ecological research based on operative in situ real-time monitoring that integrates indicators derived from multiple methodologies and observational platforms, and on the development of HAB ecological modelling.

In a multi-hazard and multi-risk perspective, a priority is to develop forecasting and early warning systems, from observation to prediction, at the same time taking advantage and making best use of existing coastal GOOS infrastructure. The detection of early stages of bloom development will facilitate risk assessment and adaptation measures, while forecasting supported by ecological modelling is a requisite for maritime spatial planning. Once again, a better organization of the information and data, so far scattered in a multitude of scientific publications or in monitoring agency reports, is requested to improve our capacity to forecast these events and implement adequate management actions to protect human health and activities.

It is worth remarking that in the Mediterranean, one overarching difficulty for risk management is that multiple human-induced pressures combine with a climate change vulnerability hotspot, e.g., increased storms and storm surges frequency and intensity, warming and marine heatwave, sea-level rise, acidification, enhanced eutrophication, invasive species, biodiversity loss, etc. as reported by Intergovernmental Panel on Climate Change-IPCC (MedECC, 2020). It is therefore necessary to begin considering the local influences of time-dependent hazards in a climate projection scenario.

The tsunami experience with the implementation of dedicated tools such as the “Tsunami Ready” program mentioned above, supporting communication to reach risks’ reduction, showcases the urgency of improving Ocean Literacy and Mediterranean Sea science communication, which can be fulfilled pivoting on the global Ocean Literacy framework for the Decade. This framework would harvest the wealth of the ongoing Ocean Literacy efforts globally and provide a voice and shared prioritization mechanisms for the global Ocean Literacy community. In this context, Ocean Literacy activities targeting *an inspiring and engaging Mediterranean Sea*, with its characteristics and specificities, have the opportunity to further flourish. Finally, in terms of capacity needs for governance to be improved and for science and technology to be properly developed and used, comprehensive education for sustainable development and public awareness are needed, together with closer involvement and collaboration of all stakeholders, including universities and research institutions but also NGOs and civil society organisations at large. The Mediterranean can count on active and resourceful networks as well as many important projects supported by the EU and several donors.

RECOMMENDATIONS FOR SCIENCE-POLICY AGENDA TO ACHIEVE THE OCEAN DECADE OUTCOMES AND FACE ITS CHALLENGES: PATHWAYS FOR SOLUTIONS AND CROSS-CUTTING PRIORITIES

This paper builds on the findings of the Decade planning workshops for the Mediterranean which took place in 2020, with particular reference to the outputs of the discussion on Decade’s outcomes as well as proposals to co-design the activities. Tailored concrete actions recommended under each outcome are presented as preliminary input to feed a major overarching science-to-policy action needed to support a transformation in the Mediterranean. Following a preliminary assessment of the available capacities, the objective is to turn the Mediterranean area into a science hub serving a “model region” where the challenge of strengthening the science-policy-society interface towards reversing the cycle of decline of the marine environment is fully tackled. This effort will explicitly point to the interconnections of pollution, climate change and hazard risk issues with the sustainability of the blue economy. Thus, it will contribute to

defining prevention, adaptive and mitigation strategies fit for the population. To this end, cross-cutting and regulatory measures need to be undertaken.

To support the reduction of pollution toward a *clean Mediterranean Sea* the level of intervention should encompass the following general measures: implement and support circular economy; optimize and reinforce monitoring to support SDG 14.1 on “reduce marine pollution”; define operational targets (nutrients and chemical reduction, discharges, single use plastics, extended producers’ responsibilities, etc.); introduce risk assessment in pollution assessments in the Mediterranean Sea; promote Ocean Literacy and citizen science. NGOs and civil society play indeed a key role in keeping pollution issues visible with the general public and also on the political agenda, a metaphorically relevant aspect if we consider that pollution is mostly hidden, e.g., in the seafloor. These sectors are key for literacy and influencing behavior modification needed to inform individual choices and environmental responsibility. Any attempts to stem global ocean pollution must deal with these regional land-derived problems as well as addressing urgency. Transportation and sinks are complex and standard guidelines must be established and toxicity understood for setting priorities. There must be an emphasis on controlling sources of pollution beside cleaning. The development of regional agreements and initiatives on sources, sinks, and types of wastes in all countries must also be a priority.

In parallel, the research actions should tackle pollution threats by better understanding the distribution, concentration and provenance of all forms of pollution focusing on source-to-sea and across sectors. This will require to:

- develop, assess and monitor plans of all sources (air/land/sea-based) of pollutants and particularly marine litter, upscaling initiatives for a clean and a healthier sea;
- address eutrophication problem developing advanced Index of Coastal Eutrophication based on in situ and satellite observation and model by determining the maximum inputs of nutrient pollution for each Mediterranean area affected by eutrophication;
- analyse pressures, status, trends and effects of hazardous substance pollution in the

Mediterranean; update the report/map of hot spots of chemical contamination, as well as the Lists of Substances of Possible Concern in the Mediterranean and Chemicals for Priority Action as contribution to existing legislation.

Pollution impact is only one among the Mediterranean Sea stressors. Conservation and protection of marine ecosystems requires boosting interdisciplinary research aimed at elucidating impacts of cumulative stressors on the ocean hence providing more complete information to fill gaps, and specify actions, aiming to improve the situation and reverse the degradation. Completing the science base with holistic mapping of the ocean, in all its dimensions, will also be needed for an adaptive management approach towards good ocean stewardship. The following pathways for solutions are identified to keep a *healthy and resilient Mediterranean Sea*:

- defining ‘restoration’ to provide scientific understanding of the future needed ocean state, creating conditions to return the Mediterranean degraded, damaged or destroyed ecosystems to their ‘functional historic trajectories’;
- understanding of structure and function of the ecosystems, spanning from the surface, through the deep sea, to benthic landscapes;
- understanding relations between reaction norm (environmental tolerance) of ecosystem structuring species and ongoing and predicted climatic changes (predicting species response, migration, and eventually extinction);
- understanding interdependencies between ecosystems across the aquatic continuum by defining baselines for structure and function in the context of understudied biogeochemical cycles, larval dispersal and populations connectivity, migratory patterns and strategies, and their relations to inter-systems links;
- identifying EOVs and sampling issues to better predict distribution and patterns by implying participatory exercises to set priorities for regional mitigation/adaptation plans;
- modelling the abrupt changes and phase shifts in ecosystem states and the impacts of unknown and emerging stressors on ecosystems;

- enlarging the management vision to the socioecological systems. Develop test cases for ecological theories benefiting from regions with accelerated paths of change and the possibility to work on a high number of diversified ecosystems; perform comparative exercises taking into account multicultural contexts, diversified socio-economic opportunities and the geopolitical diversity; pay attention to land-sea interfaces - including vulnerability;
- evaluate impacts of policy actions on restoration and management to improve understanding of the ecological trade-offs and effectiveness of MPAs to strengthen the application of effective management measures for the protection of the Mediterranean and its biodiversity;
- understanding the effects on the ecosystem of new and cumulative impacts of climate change, the growing blue economy, and geoengineering. Scaling up monitoring actions at the regional scale to collect spatial information on cumulative impacts (including on deep sea environments).

At cross-cutting level, ad-hoc formation programmes on specific mitigation/adaptive strategies addressing urgent, punctual events with high socio-economic impact (e.g., building up a regional near real time 'warning' platform' for dangerous invasive species) need to be developed and innovative technologies, e.g., related to the effective use of novel resources (particularly invasive species, such as tropical fish and invertebrates, jellyfish and seaweeds as potential food) boosted. Social sciences need to be always integrated.

Advanced monitoring approaches serving a clean, healthy, and resilient basin clearly call for a dialogue with the observing system community responsible to target *a predicted Mediterranean Sea*.

The current observing and predictive capabilities need to be sustained and to be expanded towards the biological and ecological dimension, in order to be able to observe, assess and predict related properties, as a response to alternative scenarios of climate changes and/or management policies. To address emerging scientific and societal challenges, new RIs need to be developed building on existing successful

observational/research infrastructures. Robust linkages between all types of Marine RIs (ships, stations, biology tracking, mesocosms, autonomous: gliders/floats/AUVs etc.), i.e. connected in a network of networks, should be built. Synergy (capital S) of *in situ* and space-based observation should be exploited to extend data coverage and to reduce the observational gaps of data between north and south of Mediterranean. Interoperability and opportunity opened by the big data technology will lead to integrated observing systems that are responsive and fit for purpose.

Efforts should be made to support technological innovation in observation and to improve model capabilities to predict the state of the ecosystems by:

- adopting variable spatial and temporal resolutions, according to the scale of the processes, integrating coastal and open sea;
- improving the model capability to use and upload the data coming from the new observing systems;
- integrating different processes in multiple stressors, multiple species, ecological models, hydrodynamic and Lagrangian models;
- taking full advantage of the new observational capabilities offered by present and future space missions to extend the range of observables including biological and ecological EOVs;
- integrating existing models with artificial intelligence ones to exploit big data sets;
- addressing the impact of multiple stressors (anthropogenic & natural) on ecosystems and coastal dynamics.

A well predicted Mediterranean Sea is a safer one. The integration of observatories and extension of the existing networks and European Research Infrastructures (RIs) will trigger the creation of a joint, open access, off- and onshore real-time monitoring network and hence foster the additional capacity building in a trans-disciplinary approach for the benefit of the scientific community and citizens, as well as policy makers, risk managers and stakeholders. This will support the achievement of *a safe Mediterranean Sea*.

In parallel to the establishment of an observatory network, a data infrastructure also including biological data is needed to allow the development of models, early-warning and forecasting capability. The enhancement

of forecasting capabilities is of utmost importance. In terms of capacity-building and technology transfer it is essential to encourage scientific networking for multi-hazard and multi-risk approaches. All that would allow supporting plans for adaptation and mitigation to hazardous events and climate change, to improve the preparedness of the Mediterranean region countries to emergencies, thus reducing the coastal risks, safeguarding population and socio-economic activities at sea, from an integrated perspective.

Low or incomplete and inaccurate risk perception typically leads to lack of informed risk management and of specific regulations. Reckoning these potential pitfalls and drawbacks stemming from risk perception leads to the recommendation for a stronger interaction with social scientists. Education for preparedness and awareness-raising could help trigger a more thorough risk perception and drive policy makers to plan and implement sustainable risk reduction measures.

Uncertainties are not fully considered weakening any long-term risk reduction strategy. Conversely, knowledge transfer to the society would improve risk awareness, assessment, prevention and mitigation, and long-term territorial and infrastructure renovation planning, to meet more adequate safety standards. Communicating uncertainties to stakeholders would make it easier to compare the different risks and to make informed decisions.

In terms of Ocean Literacy and social engagement, the effort to integrate different scientific disciplines, research institutions, European RIs, and stakeholders including marine operators and citizens, shall contribute to raise the societal awareness on the system complexity and the importance of science to better understand the status of marine environment and the difficulty to predict complex impacts of multi-hazards and multi-stressors affecting the basin, while promoting an integrated coastal and marine planning for risk reduction.

Attention should be also paid to the governance component of the systems, which might need to be transnational and multi-levels. The connection between existing infrastructural initiatives and intergovernmental bodies shall be fostered including a political agenda for prioritization and funding as well as frameworks for cost-sharing including a political agenda for prioritization and funding as well as frameworks for cost-sharing and partnership.

The whole process shall contribute to narrow the gap between the bordering countries of the basin, with a specific focus on developing countries, fostering an open access approach to observational and monitoring information, which are relevant for the entire Mediterranean Sea.

A shared Mediterranean Sea must be pursued also in terms of data access and transparency. Uptake of data and prediction produced by the system, and delivered in agreement with the FAIR protocols, i.e., findable, accessible, interoperable and reusable for anyone across the basin, should be maximized. Databases must prioritize the acquisition of records on productivity limits and availability of marine resources, but also including socio-economic data. Feedback from users should be considered in system continuous development.

To prevent duplication, the e-ecosystem should aim at connecting data infrastructures, without copying data and creating multiple versions of the same data, disconnected from the original source. The SeaDataNet distributed network of professional data centres, providing on-line integrated access to databases of standardized quality, mark a substantially different approach from the centralised World Ocean Database and guarantee tight connection from the data originators to the final aggregation and delivery of the observations. Additionally, SeaDataNet standards, the access and viewing services, the data formats, the metadata catalogues represent an international reference, reaching the widest adoption with the SeaDataNet Controlled Vocabulary, used in all the continents.

To sustain a robust ecosystem of data infrastructures, national engagement such as commitments from nations to participate in and use the existing data infrastructures is highly expected and recommended. National funding should maintain and update the national contribution to SeaDataNet and EMODnet.

A citation index for data sets (with persistent identifiers) to acknowledge scientists as well as institutes links directly to the repository so that users can quickly access the associated research data. Citations to data sets and studies are indexed so that their impact can be measured and their influence tracked.

A key recommendation towards a *transparent and accessible Mediterranean Sea* is to promote partnerships and agreements, in order to capitalize on previous experience and existing capabilities, through integration, consolidation, and enhancing of existing systems and efforts. This includes a fuller connection between experimental and modeler communities, in order to fuel a better connection between the models and the information acquired with novel observation systems. In a forward-looking policy orientation, the envisaged process fosters cost-effective and efficient observational and monitoring infrastructures management and forms a solid basis for further implementations, which will promote the Mediterranean Sea as a relevant science open laboratory at a global scope.

Providing open data services in the local scale according to user needs is the key to serve the knowledge-based society and boost the marine economic sectors through value addition and innovative smart data applications, which along with spatial planning tools will serve a *sustainably harvested and productive Mediterranean Sea*.

In this perspective, improving our understanding on how the blue economy sectors and climate variability impact on fisheries is the key to promote sustainable exploitation of resources, as the vast percentage of the assessed stocks is currently at an overexploited status. Special effort should be addressed to small scale fisheries, holding an important socio-economic role in the region, and contributing significantly to the structure and development of the Mediterranean coastal communities. In this context, and in collaboration with the General Fisheries Commission for the Mediterranean (GFCM), it is important to define indicators and standards of sustainability, define and study approaches and tools to identify the trade-offs between ecological dynamics and socio-economics needs by taking into account the unique characteristics of the Mediterranean social-ecological systems.

As far as energy supply is concerned, the community has recommended strategies that can help improve our capacity-development, transfer of marine technologies and innovative design solutions to promote energy transition towards renewable resources and decarbonisation, to mitigate climate change effects which are quite pronounced in the

Mediterranean. The promotion of emerging technologies, such as floating turbines and other ocean energy technologies, will improve coexistence and synergies between Offshore Renewable energy (ORE) production and other maritime sectors (e.g., aquaculture, fisheries, tourism, transport, Oil&Gas, Carbon capture and storage). Thus, new spatial management tools, such as e.g., evaluating conflicts and synergies, single and cumulative impacts, scenario building and analysis, suitability for specific uses, participatory processes and co-design, must be developed and applied to support decision making processes. In particular, they should aim at promoting the integration of MPAs in MSP and coastal management processes and the coherence between maritime and terrestrial planning as well. Moreover, as for the clean Mediterranean target, moving towards bio-economy and a circular economy framework is recommended. Hence new biotechnological solutions must be identified and exploited. Mediterranean maritime clusters (i.e., sectoral and national) shall play a major role in facilitating the exchange of knowledge, communication and best practices between public and private stakeholders and promote entrepreneurship.

The Mediterranean community must move towards the concept of a Mediterranean Sea as a shared sea, promoting the principle of the Mediterranean as "Common Sea", which contains "Common Goods", i.e. the shared and coordinated management of areas under one's own jurisdiction and of resources that have no borders. In such a context, any best practice will have an extra value to address policy and decisions in the future and help promote sustainable and balanced development of sea uses, sustainable tourism models in connection with SSF, cultural heritage, leisure boating and protected areas. Local communities and stakeholders must thus be effectively and transparently involved into national and transnational policy and decision-making processes, with the social science dimension needs to take part into the decision process. The broad community must also promote and inform the development of science-based regulatory frameworks and policies.

To reach a shared Mediterranean Sea that is sustainably harvested and productive, collaboration among existing long-term Initiatives (e.g., BlueMed and WestMED), partnerships and institutional networks and Organisations (e.g., Union for

the Mediterranean-UfM, UNEP, GFCM, Conference of Peripheral Maritime Regions-CPMR) need to be reinforced at basin and sub-basin scale. In addition, improving capacities and skills development of the new generation of marine biotechnologists, engineers, economists, touristic operators, journalists, and marine biologists, could enable future generations to contribute to a truly sustainable blue growth that can only be based on a healthy marine environment.

Outreach and awareness raising must also be pursued. In this context, Ocean Literacy actions must be taken, and we must also operate at the science/policy interface. The community needs to improve the collaboration with media in order to reinforce the communication with the general public and support science-based policy processes and harmonization, through coordination, effective implementation, optimal institutional design, monitoring and adaptation of existing Mediterranean, European and international policies.

Ocean Literacy and societal engagement have been recognized as recommended cross-cutting themes. The Decade outcome *an inspiring and engaging ocean* in the Mediterranean should help create a generation of ocean citizens and stewards capable of making science-based decisions for the protection and sustainable use of the marine environment. It will be key during the next ten years to develop actions at multiple levels and involving multiple sectors as a major opportunity to unlock the full value of human interactions, built on respect, equity, and responsibility, boost creativity in the search of ocean solutions to the world challenges, and inspire each other towards the ocean protection for sustainable development.

Recurrently, key cross-cutting recommendations have been addressed. In terms of partnerships, governance platforms for harmonization of national marine strategies of all Mediterranean Countries (e.g., EU Directives and the Barcelona Convention) need to be implemented provided the consolidation of the science-policy interface to ensure that the adopted policy options contain a robust scientific basis and that they are coherent with the SDGs. To improve transboundary partnership, vertical cooperation (coordination between the different administrative level) and horizontal cooperation (collaboration between sectors) should be enhanced.

North-South partnership deserves a specific focus. Strengthening the cooperation between the developed and developing Mediterranean countries represent a critical challenge to moderate the two-speed sustainable development which distinguishes the north and south shores. Capacity building and technology transfer is of utmost importance to foster co-designed scientific research, allocate to local scientists the needed infrastructure to conduct their research, enable policy coherence and the ecological transition in the frame of the SDGs.

Overcoming barriers such as competition, pre-conceived ideas, multi-stakeholder engagement, financial constraints, capacity issues, will improve transboundary collaboration leading to collaborative and coordinated pan-Mediterranean actions, including governance exercises to tackle complex systems and multi-cultural settings for further modelling and scaling-up.

Regional organizations could play an important role to harmonize capacity building in the region, with consideration to best practices to ensure the high quality of the training courses. Finally, social science is crucial for understanding what actions and behavior modifications would lead to desired outcomes.

CONCLUSIONS

Despite the progress made during the past years, the Mediterranean Region is still far from achieving and fully implementing the SDGs objectives. Nevertheless, as demonstrated by the previous sections, the state of the art of Mediterranean research and the long-term experience in cooperation of the community further supports the idea of the added value of developing a coordinated Regional Programme in the framework of the Ocean Decade global initiative.

“The Science We Need for the Mediterranean Sea We Want (SciNMeet)” Programme has been submitted in response to the first Call for Decade Actions as concrete proof of the willingness of the Mediterranean community to further cooperate in a global initiative, enhancing synergies and scaling-up relevant achievements reached so far. The Programme, which has been endorsed as Decade Action, aims at triggering a science driven

transformative change for the Mediterranean region by strengthening the science base related to the effect on marine ecosystems (thus goods and services) of the various stressors affecting the Mediterranean Sea, i.e. climate change, marine pollution from air/land/sea-based sources and overexploitation of marine resources, as well as of the extreme events threatening people and the environment, such as storms and tsunamis, to envision a sustainable safe and depolluted Mediterranean Sea “climatic system” (the Mediterranean Sea we want). Integration of existing initiatives and organizations and co-design have been adopted to prepare this white paper and to draft the SciNMeet Programme. Building on current relevant Mediterranean initiatives, organizations and cooperation experiences (BlueMed, UNEP/MAP, Interreg-Med, UfM, CIESM, MONGOOS, EuroGOOS, EMODnet, NEAMTWS, European Space Agency-ESA Mediterranean Sea Regional Initiative, etc.), and emerging actors, SciNMeet aims to address Decade basin challenges with a multidisciplinary, cross-sector approach, further engaging in particular the private sector. Transboundary cooperation will be pursued, and capacity development enhanced, in order to narrow the present North-South gap.

This paper has to be considered as the first step towards the preparation of the SciNMeet Implementation Plan; the second step will be to identify the projects that will contribute to the Programme since the starting time and to quantify the cost of the activities and the source of funding to contribute to its implementation in the short and long run.

On financing and support, dedicated regional funds (e.g. European Territorial Cooperation Interreg MED), European and the global-scale one (World Bank, United Nations Development Programme-UNDP) need to be integrated to complement national investments. Mobilize financing, having the Ocean Decade visible in the national agenda, enhance national implementation and strengthen institutions are the key to achieve the Goals by the target date of 2030, leaving no one behind.

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