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REVIEW
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Challenges for Sustained Observing and Forecasting Systems in the Mediterranean Sea

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The Mediterranean community represented in this paper is the result of more than 30 years of EU and nationally funded coordination, which has led to key contributions in science concepts and operational initiatives. Together with the establishment of operational services, the community has coordinated with universities, research centers, research infrastructures and private companies to implement advanced multi-platform and integrated observing and forecasting systems that facilitate the advancement of operational services, scientific achievements and mission-oriented innovation. Thus, the community can respond to societal challenges and stakeholders needs, developing a variety of fit-for-purpose services such as the Copernicus Marine Service. The combination of state-of-the-art observations and forecasting provides new opportunities for downstream services in response to the needs of the heavily populated Mediterranean coastal areas and to climate change. The challenge over the next decade is to sustain ocean observations within the research community, to monitor the variability at small scales, e.g., the mesoscale/submesoscale, to resolve the sub-basin/seasonal and inter-annual variability in the circulation, and thus establish the decadal variability, understand and correct the model-associated biases and to enhance model-data integration and ensemble forecasting for uncertainty estimation. Better knowledge and understanding of the level of Mediterranean variability will enable a subsequent evaluation of the impacts and mitigation of the effect of human activities and climate change on the biodiversity and the ecosystem, which will support environmental assessments and decisions. Further challenges include extending the science-based added-value products into societal relevant downstream services and engaging with communities to build initiatives that will contribute to the 2030 Agenda and more specifically to SDG14 and the UN's Decade of Ocean Science for sustainable development, by this contributing to bridge the science-policy gap. The Mediterranean observing and forecasting capacity was built on the basis of community best practices in monitoring and modeling, and can serve as a basis for the development of an integrated global ocean observing system.

Keywords: observing and forecasting systems, sustained observations, ocean variability, FAIR data, climate, operational services, science with and for society, SDG's

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Abbreviations: ADCP, Acoustic Doppler Current meter Profiler; Argo, Global array of subsurface profiling floats; BiOS, Bimodal Oscillation System; CALYPSO, Coherent Lagrangian Pathways from the Surface Ocean to Interior; CMEMS, Copernicus Marine Environment Monitoring Service; CAPEMALTA, Meteo and marine operational forecasting system for the Maltese Islands; CTD, Conductivity Temperature Depth; CYCOFOS, Cyprus Coastal Ocean Forecasting System; EOV, Essential Ocean Variable; EU, European Union; CO_2, Carbon dioxide; CSIC, Spanish National Research Council; DEKOSIM, Center for Marine Ecosystems and Climate Research; EMODnet, European Marine Observation and Data Network; EOOS, European Ocean Observing System; EuroGOOS, European Global Ocean Observing System; FAIR, Findable, Accessible, Interoperable, Re-Usable; FB, Ferrybox system; GCOS, WMO Global Climate Observing System; GEO, Group on Earth Observations; GitHub, A web-based hosting service for software development projects that use the Git revision control system; GIS, Geographic Information System; GOOS, Global Ocean Observing System; GTS, Global Teleconnection System; ICCAT, International Commission for the Conservation of Atlantic Tunas; IEO, Spanish Institute of Oceanography; IEOOS, IEO Observing system around Spanish mainland, the Canary and the Balearic Islands; Ins-TAC, the *In Situ* Thematic Assembly Center; IOC, Intergovernmental Oceanographic Commission of UNESCO; IODE, IOC International Oceanographic Data and Information Exchange; IPCC, International Panel Climate Change; ISO, International Standards Organization; IOLR, Israel Oceanographic & Limnological Research; ISRAMAR, Israel Marine Data Center; LDCs, Least Developed Countries (LDCs); MAOS, Mobile Autonomous Oceanographic Systems; MARIA, Atmospheric and wave forecasting system for the Sicilian Channel; Med-Argo, Argo Regional Center for the Mediterranean; Med-MFC, CMEMS Mediterranean Monitoring and Forecasting Center; MONGOOS, Mediterranean Oceanography Network for Global Ocean Observing System; MOOSE, Mediterranean Ocean Observing System for the Environment; NODC, National Oceanographic Data Centers; ODYSSEA, Operating a Network of Integrated Observatory Systems in the Mediterranean Sea; PORTUS, *Puertos del Estado (in Spanich)* System; POSEIDON, HCMR monitoring and forecasting system; QA/QC, Quality Assurance/Quality Control; RADMED, *Radiales Mediterráneo (in Spanish);* REMPEC, Regional Marine Pollution Emergency Response Center for the Mediterranean Sea; RITMARE, Ricerca ITaliana per il MARE; ROOS, Regional Ocean Observing System; ROSARIO, Malta shelf thermo-hydrodynamic forecasting sysyem; R/V, Research Vessel; SAMOA, *Sistema de Apoyo Meteorológico y Oceanográfico a las Autoridades portuarias in Spanish.*; SANIFS, Southern Adriatic Sea and Northern Ionian Forecasting System; SeaDataNet, Pan-European infrastructure for ocean and marine data management; SE LB, South Eastern Levantine Basin; SDG(s), Sustainable Development Goal (s); SDG14, Sustainable Development Goal 14: Life below the sea; SDG13, Sustainable Development Goal 13: Climate action; SeaDataCloud, Further developing the pan-European infrastructure for marine and ocean data management; SELIPS, South

INTRODUCTION

The Mediterranean Sea is an ideal laboratory for studying ocean processes of global relevance, such as water mass formation, overturning circulation, boundary currents, meso/submesoscale eddies and instabilities, carbon export and associated ecosystem responses (Pinardi et al., 2006; Malanotte-Rizzoli et al., 2014). The Mediterranean is one of the most vulnerable regions in the world due to the impacts of climate change (e.g., alterations in the overturning circulation; extreme wave heights and warming, sea level rises, storm surges, acidification, oxygen depletion, invasive species, etc.), and its precarious socio-economic conditions and fragile political systems, particularly in more vulnerable southern shore countries.

From a societal perspective, stakeholders across the Mediterranean Sea (harbors and marinas, fisheries and aquaculture, oil companies, maritime transport, civil protection, tourist resorts, environmental agencies, research institutions, citizen associations, etc.) are already aware of the potential benefit of establishing an ocean observing and forecasting system. Establishing a sustained Mediterranean system is therefore timely and stakeholders have already recognized the importance of embracing the entire value-adding ocean chain, from observations to forecasts and customized products, thus providing the foundations for a sustainable Blue Economy compliant with the UN's Sustainable Development Goals (SDG).

The Mediterranean research community has organized several programmes and projects to develop the end-to-end system, which will contribute mainly but not only to the UN SDG13 (Climate Action) and SDG14 (Life Below Water) goals and the Sendai Framework for Disaster Risk Reduction. A good example is the well-established Mediterranean modeling system, which is structured around the Copernicus Marine Environment Monitoring Service (CMEMS) and national and sub-regional downscaled forecasting systems, with numerous high-quality applications providing user-oriented services. In addition, advanced multi-platform and integrated observing systems are continually being developed and implemented by universities, research centers, European research infrastructures and private companies facilitating mission-oriented innovation that feeds into CMEMS (Le Traon et al., 2019) and the EMODnet programme (Martín Miguez et al., 2019).

Thus, the community can respond to science priorities, societal challenges and stakeholders needs, developing a variety of fit-for-purpose products. The combination of state-of-the-art observations and forecasting models provides new opportunities for downstream services in response to the needs of the heavily populated Mediterranean coastal areas. However, the observing and forecasting system has various deficiencies and shortcomings, such as:

- The lack of sustained *in-situ* observations for several Essential Ocean Variables (EOVs) and sometimes poor data policy, particularly in the Central-Eastern Mediterranean and on the Northern African coasts.
- The diversity of the forecasting models is limited and their skills have not been fully assessed yet;
- There is little connection between the development of the satellite observing system and situ components, which is in many instances hampering the opportunity to extend the range of observables from space. Satellite observations cover the entire Mediterranean but only provide surface information and at scales that are not of high enough resolution to capture the fine-scale processes that characterize the high temporal and spatial variability of this basin.
- Existing networks are only supported by national research funds and their long-term sustainability is at risk. Coordination and basin-scale integration is difficult, particularly across-disciplines (e.g., fishery data collection vs. physics and biogeochemistry).
- Communication with the wide range of regional policy stakeholders is generally lacking and requires development.

The Mediterranean observing and forecasting systems are part of a larger ocean value chain that links observations to applications of societal benefit. This value chain can be subdivided into the "basic" or "core" systems/services, which are mainly related to observations and forecasting products/infrastructures, and "downstream" services that generate customized products for policy makers, industry and the general public. The "basic" infrastructure is essential for the downstream services, and it must run smoothly and have a fully open and free data policy.

The aim of this paper is to review the current status of the Mediterranean Sea environmental and climate challenges and document the present observing and forecasting system organization and the downstream services, resulting in an analysis of the gaps and deficiencies. Solutions are then proposed, with a special focus on the challenges to be faced over the next decade. In section Mediterranean Sea Environmental and Climate Challenges, the major Mediterranean Sea environmental and climate challenges are discussed, and the basic systems including the Mediterranean Oceanography Network for Global Ocean Observing System (MONGOOS) collaborative framework are presented in sections Basic Systems and Services and MONGOOS Collaborative Framework. Section Downstream Services in Response to Societal Challenges and Stakeholders provides examples of the downstream services in place. Section Gaps and Prospects for the Next Decade gives a description of the gaps and future actions, and section Conclusions concludes.

MEDITERRANEAN SEA ENVIRONMENTAL AND CLIMATE CHALLENGES

In the last few decades, anthropogenic pressures (e.g., climate change, local pollution, tourism, fisheries, maritime transport, etc.) on the Mediterranean ecosystems have increased. As a consequence, significant and likely irreversible changes are

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Eastern Levantine Israeli Prediction System; SISCAL, Satellite-based Information System on Coastal Areas and Lakes; SISMER, *Systèmes d'informations scientifiques pour la Mer (in French);* SKIRON, Operational Atmospheric Forecasting System; SOCIB, Balearic Islands Coastal Ocean Observing and Forecasting System; SST, Sea Surface Temperature; SeaDataNet, Pan-European infrastructure for ocean & marine data management; SWOT, Surface Water and Ocean Topography; TAC, Thematic Assembly Center; WMO, World Meteorological Organization; WAM, Wave Model; WRF, Weather Research and Forecast atmospheric Model.

occurring in Mediterranean waters including the warming of deep waters, increased anthropogenic carbon dioxide inputs and uptake, acidification and biodiversity loss. Such factors are severely damaging the ecosystems in surface and intermediate/deep waters and marine habitats as a whole.

The recent Ocean State Report from the Copernicus Marine Environment Service (von Schuckmann et al., 2018) stated that the sea surface temperature between 1993 and 2016 in the Mediterranean has increased by 0.04 ± 0.004°C per year, which is the second largest trend in the European regional seas after the Black Sea. Sea surface salinity also increased 0.01 PSU per year average over the whole basin in the same time period. The sea level has increased by 2.7 ± 0.9 mm per year, comparable to the increase in the North West Shelf and Black Sea but less rapidly than the Baltic Sea and the global ocean, probably due to the salinity trend and the hydrological cycle changes but also to the specific semi-enclosed nature of the basin (Pinardi et al., 2014).

The Mediterranean Sea has also been identified as an important anthropogenic carbon pool where the column inventory is much higher than in the Atlantic (Álvarez-Berastegui et al., 2016; Schneider et al., 2018). This is due to its intrinsic physico-chemical characteristics, in which warm and highly alkaline waters are prone to absorb high amounts of CO_2 from the atmosphere and transport it to deep waters via a number of convective areas. However, the variability of inorganic carbon remains unknown, given the lack of observations of the carbonate system at present. While at the global scale CMEMS models simulate a relatively stable ocean carbon uptake during the 1990s and a sharp increase since the beginning of the 2000s, the Mediterranean Sea appeared to act as a weak sink over the last decade (-3.5 gC/m^2/year in 2016, von Schuckmann et al., 2018).

The time-mean circulation is now well known (**Figure 1**) from both reanalysis and observations (Rio et al., 2014; Pinardi et al., 2015; von Schuckmann et al., 2016). It is composed of multiscale structures, such as basin-scale gyres, intensified boundary currents, open ocean intensified jets and recurrent and reversing gyres (Font et al., 1988; Poulain et al., 2007; Pinardi et al., 2015). A well-documented intense climatic event occurred in the nineties, the so-called Eastern Mediterranean Transient (EMT, Klein et al., 1999), which radically changed the deep-water properties of the basin. This is the only event of its kind, captured during a basin-scale survey carried out in the 1990s. The change involved a reversal of the Northern Ionian Sea circulation, also called the Adriatic-Ionian Bimodal Oscillation System (BiOS, Gačić et al., 2011), which was found to be correlated to wind stress curl changes (Demirov and Pinardi, 2002; Nagy et al., 2019). These changes are specific to the Mediterranean Sea and had a significant impact on the ecosystem functioning at the basin scale (Danovaro et al., 2001).

In the Western Basin, a second climatic anomaly known as the Western Mediterranean Transient (Schroeder et al., 2016) began between 2004 and 2006 during very cold winters. It was induced by intense heat flux losses and deep water formation in the Gulf of Lion (Schroeder et al., 2008), leading to an abrupt increase of temperature and salinity in deep waters and thus accelerating the trends observed over the past 40 years (Borghini et al., 2014). It also resulted in an anomalous stratification of the deep-water column due to the superposition of newly formed warmer and saltier deep waters (Schroeder et al., 2016). The outflow of these waters through the Strait of Gibraltar is detectable in late winter-early spring (García-Lafuente et al., 2011; Sammartino et al., 2015) and it was clearly identified a decade later (Naranjo et al., 2017). Repeated glider missions along the Ibiza Channel endurance line have provided key semi-continuous observations, from which the variability of the meridional exchanges in the Western basin and its relation to surface and intermediate water mass changes can be monitored (Heslop et al., 2012; Juza et al., 2019).

From a biogeochemical point of view, the Mediterranean Sea has relatively high O_2 concentrations in deep waters, caused by intense ventilation mechanisms resulting from winter deep ocean convection processes (Schneider et al., 2018). In the intermediate layer occupied by the Levantine Intermediate Water (LIW), a minimum oxygen layer (OML) is present throughout the Mediterranean Sea. With global warming, these concentrations have become very sensitive to an overall decrease in O_2, as predicted by climate and biogeochemical models, particularly in response to an increase in water column stratification (Oschlies et al., 2008). However, the energetics of the basin circulation have recently been studied and it was found that both buoyancy and wind inputs contribute to invigorating the total energy of the circulation, thus providing evidence of the basin's intrinsic resilience to de-oxygenation processes (Cessi et al., 2014). In the past the Mediterranean is known to have been prone to large deoxygenation events, known as sapropels (Negri et al., 2009).

The N/P ratios in the Mediterranean deep waters are higher than in the global ocean (about 24:1 vs. 16:1) with a marked horizontal gradient from west to east (Bethoux et al., 2002). This is explained by a preference for phosphate consumption over nitrate by phytoplankton, indicating a phosphate limitation, particularly in the eastern basin (Thingstad et al., 2005; Pujo-Pay et al., 2011). More recent studies have highlighted the significant contribution of anthropogenic inputs of (N,P) through the atmosphere and rivers to surface and intermediate waters in the Mediterranean (Cossarini et al., 2012), and a high variability of surface nutrients related to the variability of the mixed layer depth, particularly in the Western basin (Pasqueron de Fommervault et al., 2015). The Mediterranean is also known to be an oligotrophic basin with some intermittent bloom regions (D'Ortenzio and Ribera d'Alcalà, 2009; Mayot et al., 2017) but the general trend is not clear. Some future scenarios predict an increase of nutrients gradients whereas others suggest a homogenization of bio-regions toward oligotrophy or eutrophication (Lazzari et al., 2014; Colella et al., 2016).

Basin wide, the Mediterranean Sea is a region of significant fronts, mesoscale and submesoscale variability (Pascual et al., 2013; Bosse et al., 2017; Testor et al., 2018), which regulate the exchanges between the open sea, the shelves and the coastal areas (Pinardi et al., 2006; Jordi et al., 2008) although at smaller scales than in other parts of the global ocean, given the Sea's small Rossby radius (Escudier et al., 2016b; Barcelo-Llull et al., 2019). Such mesoscale-submesoscale variability (McWilliams, 2016) drives the vertical exchanges between the upper layers and

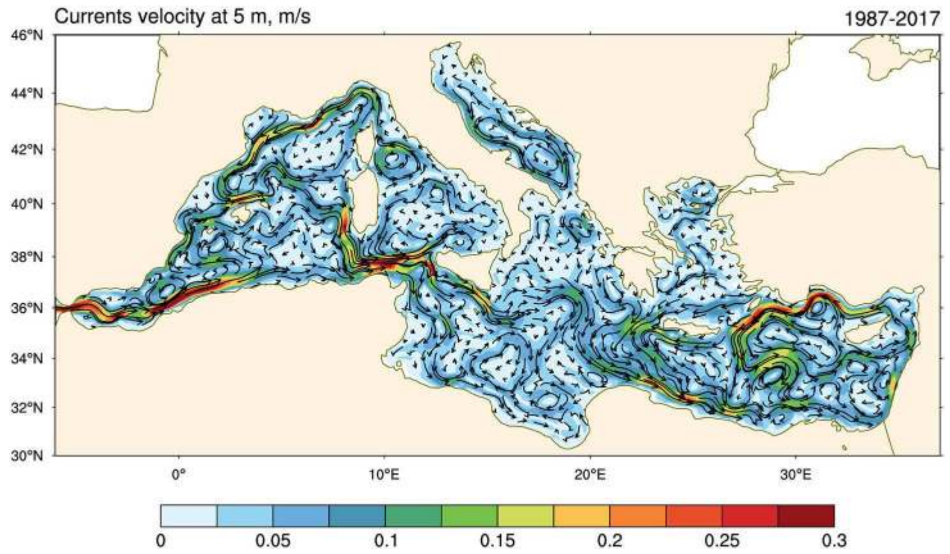

FIGURE 1 | The time mean circulation from CMEMS reanalysis (period 1985–2017, product MEDSEA_REANALYSIS_PHYS_006_004). The velocity field is visualized by curved arrows overlaying the amplitude of the currents (m/s) in color. The detailed description of this circulation picture is offered in Pinardi et al. (2015) and an update is given in von Schuckmann et al. (2016).

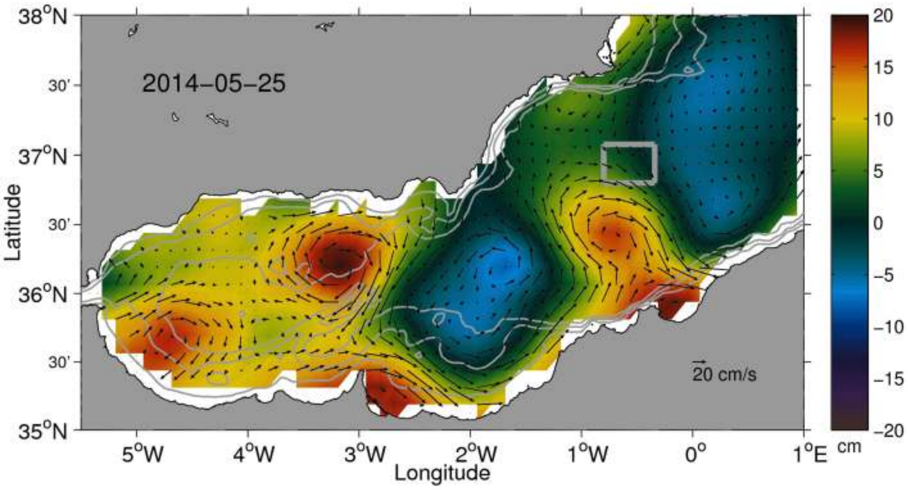

FIGURE 2 | Absolute dynamic topography and associated geostrophic currents for 25 May 2014 derived from gridded altimetry fields (CMEMS). The gray box corresponds to the domain sampled during the AlborEx experiment in the eastern Alborán Sea aimed at understanding meso- and submesoscale processes in an intense front [from Pascual et al. (2017)].

the deep ocean (**Figure 2**, Tintoré et al., 1991; Pascual et al., 2004; Ruiz et al., 2009) and in particular the supply of nutrients to the euphotic zone (Mahadevan, 2016; D'Asaro et al., 2018). Given the ideal conditions of the Alborán Sea in the Western Mediterranean (Ruiz et al., 2009, 2018; Pascual et al., 2017) the international programme CALYPSO[1] was established in 2018 to provide an understanding and predictive capability of the three-dimensional coherent pathways by which water carrying tracers and drifting objects is transported from the surface ocean to depths below the mixed layer.

The heat and drought waves are also major challenges in terms of the water availability and preservation of marine ecosystems in the Mediterranean (Vautard et al., 2007). The risk of extreme heat waves in Europe, like the unprecedented event in the summer of 2003, is likely to increase in the future, and requires further understanding of their potential predictability and possible mitigation. Extensive mass mortality in benthic communities was registered after the 2003 heat event (Olita et al., 2007; Garrabou et al., 2009) and heat waves are now understood to boost harmful algal blooms (HAB) (Joehnk et al., 2008). There is also a general concern that jellyfish are becoming more prevalent in many regions around the Mediterranean Sea

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[1] https://calypsodri.whoi.edu

(Shiganova et al., 2001; Kogovsek et al., 2010; Prieto et al., 2015). Jellyfish have a significant impact on coastal economic activity and on the important tourism industry of the Mediterranean region (accounting for 15% of global tourism) (Ciscar et al., 2001), but no systematic, scientific based monitoring system at basin scale has been implemented (Prieto et al., 2015).

The sustainability of marine living resources is also a major challenge in the Mediterranean. Most of the fish stocks (78%) monitored by the General Fisheries Commission for the Mediterranean are overexploited (FAO 2018). Sustained monitoring could play a key role in knowledge-based fisheries management and ecosystem conservation. The recovery of the Eastern Atlantic bluefin tuna population during the last decade, after a long period of continuous and alarming decrease, is a successful example of how science and operational oceanography can trigger advances in the sustainability of fisheries and species conservation. At SOCIB, the combination of hydrodynamic models, remote sensing and *in situ* data has enabled the development of techniques for predicting both the spawning and larval habitat distribution, and the survival rate of the egg and larvae in the Balearic Sea (Álvarez-Berastegui et al., 2016; Reglero et al., 2018). These novel predictive capabilities have been applied to the standardization of larval abundance indices used to evaluate the trends of adult tuna populations during the last two decades (Ingram et al., 2017; Álvarez-Berastegui et al., 2018a), and to integrate environmental variability into the short-term forecasting of the survival of larvae and the derived immature individuals. The International Commission for the Conservation of Atlantic Tunas (ICCAT) applies these methods to establish the annual fishing quotas for bluefin tuna and Mediterranean albacore tuna.

The Mediterranean Sea is also affected by tsunami-frequency sea level changes, which are not triggered by seismic activity but driven by air-pressure disturbances that are often simultaneous to fast-moving perturbations, such as thunderstorms, squalls, and other storm fronts. These episodes, called meteo-tsunamis (e.g., Vilibic et al., 2016), have been reported in Croatia, the Balearic Islands, Sicily, Malta and Greece. Specifically, Croatian islands and Menorca are where the highest magnitudes of meteotsunamis have been observed worldwide (6- and 4-m oscillations, respectively). Meteotsunamis generate flooding and are associated with very strong currents (up to 4 m/s), cause serious economic damage to ships and harbor installations and can travel long distances and influence a very long area of coastline (Masina et al., 2017; Picco et al., 2019).

Floating plastic pollution tend to concentrate on convergences acting as retention areas and in eddies and fronts at lower scales (Maximenko et al., 2012). In a recent study based on numerical simulations of plastic transport, Liubartseva et al. (2019) identify the potentially most polluted areas in this Sea from a series of anthropogenic sources, which confirm that the highest concentration of plastic is found near continental shores (Collignon et al., 2014; Ruiz-Orejón et al., 2016, 2018). Information is still limited but Eriksen et al. (2014) estimated floating plastic debris in the Mediterranean as 23,150 tons, with 3,056 corresponding to micro- and nano-plastics, which mirrors the 1,500 tons estimated from samples obtained by Ruiz-Orejón et al. (2016). Biodiversity is highly affected by marine litter, either through entanglement, ingestion or colonization (Deudero and Alomar, 2015; Fossi et al., 2018). There is even a certain overlap between the feeding areas of diverse marine species and the convergence zones of floating microplastics (Fossi et al., 2017). Thus, observing and forecasting systems are essential in providing tools to understand the effects of plastics on species and ecosystems and to achieve the Good Environmental Status (GES) as set out in the European Marine Strategy Framework Directive (MSFD) (Galgani, 2019). The hazard mapping recently conducted by Compa et al. (2019a), which correlates litter with species distribution maps in the Mediterranean basin, is an interesting approach. Other potential observing systems for marine litter are the cleaning coastal vessels that provide densities, distribution and temporal patterns of floating marine macrolitter along coastal systems such as in the Balearic Islands (Compa et al., 2019b).

All these issues require a scientific basis for the understanding, monitoring and modeling of the Mediterranean Sea marine environment, and a collaborative international framework to design and implement the basic services in support of the downstream sector. The existing monitoring and forecasting system that have been developed over the past 20 years for operational oceanography need to be expanded to biochemical EOVs, and toward applications that will offer solutions for climate mitigation and adaptation, biodiversity conservation, decreased ocean pollution and more accurate met-ocean forecasts for disaster risk reduction.

BASIC SYSTEMS AND SERVICES

As described in the introduction, basic systems produce "generic" products ready to be ingested by downstream services. The basic system infrastructure is composed of observing systems, forecasting and data assembly systems. In the following we describe each component in the Mediterranean Sea basic infrastructure.

Multi-Platform Observing Systems

Most of the present European regional observing systems described in this section have their origin in the coordinated efforts that started in the early nineties in the Mediterranean Sea, due to EU strategic planning and associated funded projects. This has led to a well-structured and reasonably coordinated community that feeds real-time and delayed mode quality-controlled data into the different European portals, in particular through the CMEMS Mediterranean Monitoring and Forecasting Center (Med-MFC), the *in situ* Thematic Assembly Center (Ins-TAC, Petit de la Villeon et al., 2018) and EMODnet. However, the funding for the observing components is in most cases of only national origin and the sustainability of these key initiatives is a critical issue and an important concern.

MOOSE

In 2010, a Mediterranean Ocean Observing System for the Environment (MOOSE[2]) was implemented in France as an integrated observing network of the NW Mediterranean Sea.

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[2] http://www.moose-network.fr

MOOSE objectives include the detection and identification of environmental anomalies via both long-term monitoring and near real-time measurements capabilities.

The MOOSE strategy is based on multisite and multi-platform continuous observations from the coast to the deep sea. It combines Eulerian observatories and autonomous Lagrangian platforms to collect the EOVs and is open to new approaches based on omics and modern imagery techniques, which can better address the emerging issues in marine ecology. It is designed to detect and monitor seasonal or inter-annual variability, and the impact of extreme events that control physical and biogeochemical fluxes and marine biodiversity. MOOSE also provides a large flow of real-time data to facilitate the validation of operational oceanographic models. The MOOSE strategy is based on an *in-situ* observing system, capable of capturing all scales of variability, thus avoiding any aliasing effects caused by sub-sampling. Thus, MOOSE aims to address scales of variability ranging from the very small (1 km horizontally, over a few days) to the basin scale (500 km, months/years), passing by the mesoscale (15 km, weeks/months). The MOOSE components are (**Figure 3**):

- Two river observatories (Rhône, La Têt)
- Three observatories for atmospheric deposition (Cap Béar, Frioul, Cap Ferrat)
- Two moorings in canyons (Lacaze-Duthiers, Planier), which are complimented by three open sea moorings from EMSO network (Lion, Dyfamed, and Albatross)
- Two HF radars (Toulon, Nice)
- Monthly and annual ship visits (Mola, Antares, Dyfamed, and MOOSE_GE)
- Two glider endurance lines along the north-south sections (Marseille-Minorca, Nice-Calvi)

Marine observations are accomplished by combining observations from fixed (deep moorings and buoys) and Lagrangian platforms (Argo floats and gliders) which are completed with ship surveys both in the coastal and open sea regions. In the MOOSE network, two glider endurance lines are currently in operation: Villefranche-Dyfamed-Calvi and Marseille-Lion-Menorca.

Deepwater convection processes and their interaction with dense shelf water cascading events modify deepwater mass properties and deep sediment resuspension in the Gulf of Lion (Durrieu de Madron et al., 2013). Over the past decade, the MOOSE network has documented a slow increase in deepwater temperature, punctuated by very rapid warming, leading to even warmer and saltier deep waters. The absence of intense convection reinforces the oxygen minimum signature in the intermediate waters, especially in the Ligurian Sea where the winter mixing and ventilation are less intense than in the Gulf of Lion (Coppola et al., 2018).

Regular and long-term monitoring in the MOOSE network has provided significant results that can be used to interpret the temporal variability of nutrients and the zooplankton community, which are sensitive to deep vertical mixing events (Donoso et al., 2017). Coastal observations showed that the long-term evolution of nutrient inputs here is driven by Rhône River water discharges, which respond differently depending on whether a climatic or an anthropogenic forcing occurs (Cozzi et al., 2018).

SOCIB

The Balearic Islands Coastal Ocean Observing and Forecasting System (SOCIB[3]) is a Marine Research Infrastructure, a multi-platform and integrated ocean observing and forecasting system that provides streams of data, added value products, and forecasting services from the coast to the open ocean (Tintoré et al., 2013). It was initiated in 2008 and since 2014 it is included in the Spanish Large-Scale Infrastructure Map. SOCIB aims to characterize ocean state and variability at different scales, from local to submeso-mesoscales and from nearshore and regional to large basin scales, on temporal ranges that span from events to climate.

Figure 4 shows the SOCIB network of observing infrastructures for long-term monitoring and for dedicated deployment during open access intensive multi-platform process-oriented studies. The network includes satellite-tracked surface and profiling drifters (through an annual deployment of 3 Argo floats[4] and 8 SVP drifters), 16 autonomous fixed coastal stations deployed around the Balearic Islands, 2 met-ocean moorings located in the Ibiza channel and the bay of Palma, a 24 m coastal research vessel, 2 high-frequency radar stations overlooking the Ibiza Channel, a fleet of 7 autonomous underwater gliders and 2 beach monitoring stations. More specifically, SOCIB runs a glider endurance line in the Ibiza channel (a well-established biodiversity hot spot) to monitor the north-south exchanges and their relation to the variability of the circulation, of the different water masses and the associated ecosystem variability. Animal-borne instruments are a new addition to SOCIB and since 2015, tracked sea turtles complement the observing system with unique and cost-effective data (Patel et al., 2018) providing information on essential biodiversity variables and contributing to knowledge based marine conservation (Boehme et al., 2009). Complementary to this quasi-real time network, high-resolution beach bathymetries and sediment samples surveys, multidisciplinary seasonal oceanographic surveys in the Ibiza and Mallorca Channels and glider sections to Algeria and Sardinia are performed periodically, providing long-term observations that allow quantification of the variability, changes and trends in beach morphology, water mass transformation, mass and heat transport and content, eddies structure and variability, etc.

All SOCIB data are made available in near real time for scientists and society under the terms of an open access policy, in line with European initiatives such as Jericonext (Farcy et al., 2018). The data, scientific production, outreach and engagement activities, as well as tools and products developed are a clear performance indicator of SOCIB achievements and innovations in the new era of ocean observation. The alignment of these elements is possible due to a dedicated data lifecycle management that is fully committed with the Findable,

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[3] www.socib.es

[4] Contribution to EuroArgo ERIC.

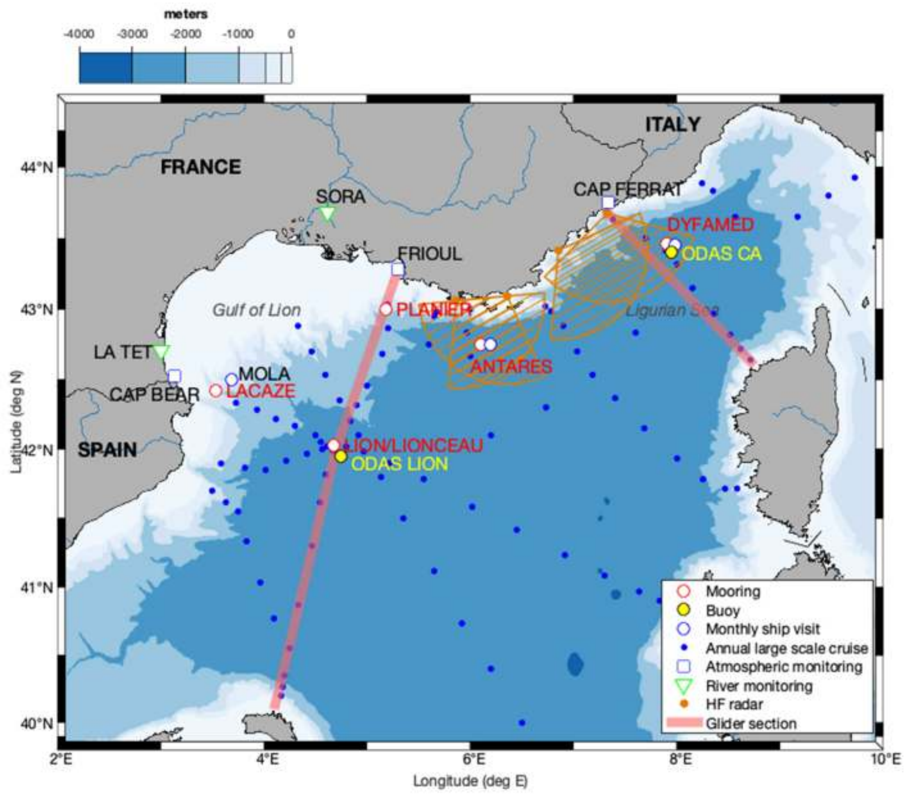

FIGURE 3 | The MOOSE observatory components including the EMSO open sea moorings.

Accessible, Interoperable and Reusable (FAIR) data principles (Wilkinson et al., 2016) and that also contributes to the IOC Ocean Best Practices System[5] (Pearlman et al., 2019).

From the SOCIB perspective, the real challenge for the next decade is the full integration of these technologies and multi-platform observing and forecasting systems. As a research infrastructure, SOCIB in partnership with CSIC and IEO scientists, combines operational, scientific and training activities. SOCIB and similar infrastructures worldwide, due to their scientific excellence, critical mass, multidisciplinary, integrated and targeted approach, open data policy and sustained funding, are establishing new research ecosystems that facilitate mission-oriented innovation. Further details are provided section SOCIB Innovation, Products and Services.

The SOCIB observing system has contributed to, the understanding of the relationship between the north-south internannual exchanges and the water masses vertical structure (Heslop et al., 2012; Barcelo-Llull et al., 2019; Juza et al., 2019), the understanding of the dynamics of meso and submesoscale eddies and their impact on the circulation (Escudier et al., 2016a) and biogeochemical fluxes (Cotroneo et al., 2016; Pascual et al., 2017; Aulicino et al., 2018) and to the sustainability of Bluefin tuna in the Mediterranean (Álvarez-Berastegui et al., 2018b). On the coastal and nearshore area, SOCIB has contributed to unravel the beach response to storminess and sediment budget dynamics in Mediterranean beaches (Morales-Márquez et al., 2018; Gómez-Pujol et al., 2019).

POSEIDON

POSEIDON[6] was established in 1997 as a research infrastructure of the Eastern Mediterranean basin for the monitoring and forecasting of the marine environment. It supports the efforts of the international and local community and addresses the requirements of science, technology and society. The general aims are (a) to establish a sustainable marine observing network in the Eastern Mediterranean, (b) to provide quality and validated forecasts of the marine environment, (c) to provide scientific knowledge and support for the study of ocean mechanisms and their variability and to address the sensitivity of marine ecosystem and biodiversity combining natural forcing factors and anthropogenic pressures, and (d) to provide a technology test bed and services to marine policy-makers and society.

The system is being developed in accordance with the policy frameworks suggested by GOOS, EuroGOOS, MonGOOS, and GEO, while maintaining a balance between the operational and research characteristics of the infrastructure through the integration of methodologies and tools developed in relevant EU initiatives and projects. The data provided by POSEIDON in the Aegean and Ionian Seas sample a wide area. The present (2018) status of the POSEIDON observatory includes multiple platforms

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[5] www.oceanbestpractices.org

[6] www.poseidon.hcmr.gr

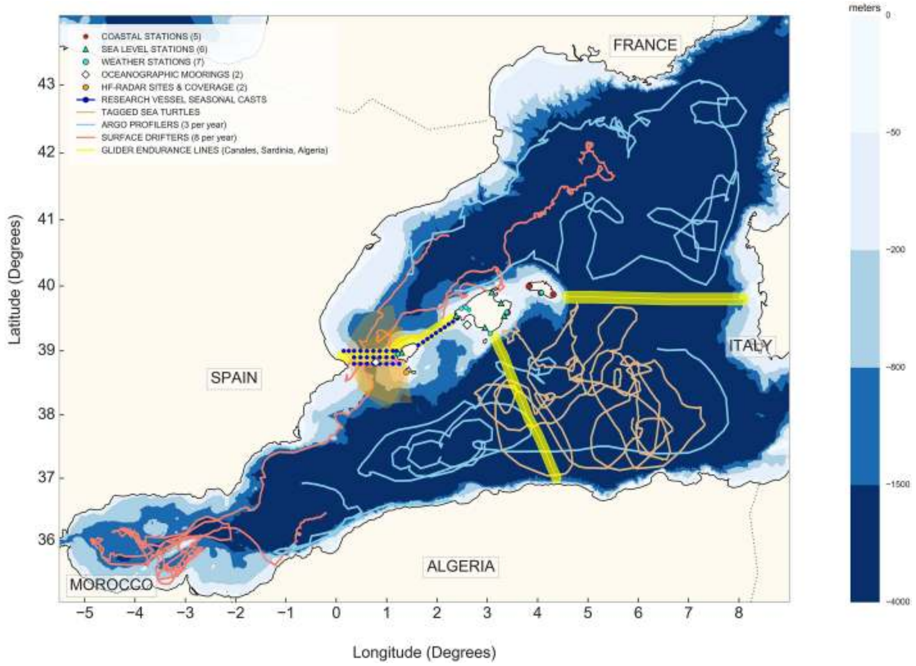

FIGURE 4 | The components of SOCIB Multiplatform Observing Infrastructures as of 2019, extending from the coast and the nearshore Balearic beaches, to the coastal and open sea, and including contributions from SOCIB to EuroArgo ERIC and Jericonext. The glider endurance line toward Sardinia is jointly operated between CNR-ISMAR and SOCIB.

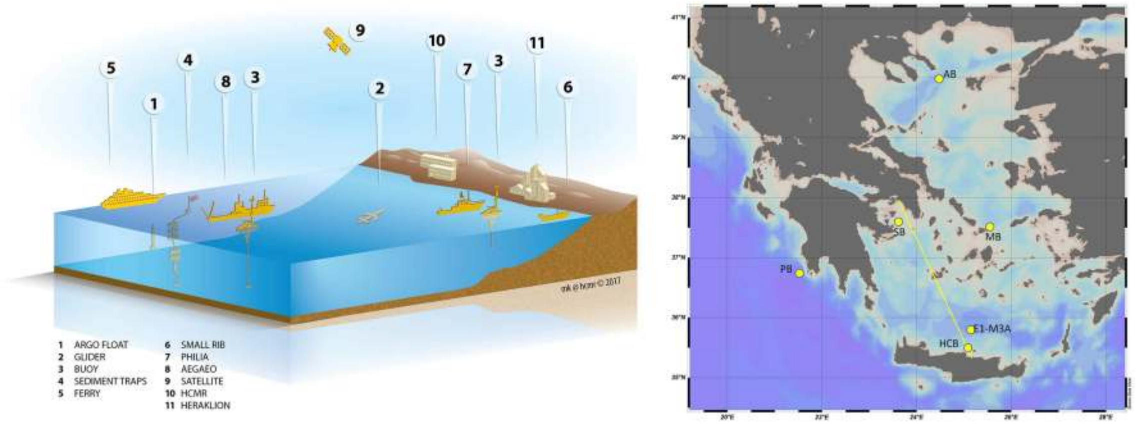

FIGURE 5 | Left: Platforms of Poseidon observatory. Right: Map showing the location of the POSEIDON system fixed platforms (AB, Athos Buoy; MB, Mykonos Buoy; PB, Pylos Buoy; SB, Saronikos Buoy; E1-M3A Buoy) and Ferrybox route (yellow line) [from Petihakis et al. (2018)].

(**Figure 5**) operating at various spatiotemporal scales (**Figure 6**). The components are:

- Three wavescan buoys are deployed in the S. Aegean (E1-M3A), N. Aegean (ATHOS) and Ionian waters (PYLOS) provide meteorological, physical and biochemical (O_2, Chl-a) data (Petihakis et al., 2018).
- A Ferrybox system (FB) operating on the route connecting the ports of Piraeus (Athens) and Heraklion. This fully automated, flow-through system includes sensors of temperature, salinity, fluorescence, turbidity and pH. FB has been proven to be a helpful tool in the study of water circulation (e.g., modified Black Sea Water flowing in the Aegean Sea), in particular when assimilated into prognostic numerical circulation models to improve their accuracy (Korres et al., 2014).
- Sampling of seawater and plankton, which is regularly conducted next to the fixed biochemical platforms and on board the FB. R/V visits are made monthly next to the E1-M3A site and the HCB.
- The Greek Argo infrastructure (www.greekargo.gr), which had 15 deployed floats in 2015 and 2016 (five of which were BGC-Argo) and aims for a total of 25 Argo floats, further contributes

to the international Argo community efforts to monitor the Eastern Mediterranean region.

- Interaction with several land-based facilities located nearby the observatory, which is necessary for sensor maintenance and the analysis of discrete samples. The calibration lab, micro- and mesocosms, meteorological stations, and atmospheric deposition station are also key land-based components. In particular, the calibration lab, considering the local environmental conditions, is a powerful tool for the calibration of sensors deployed in the wider Mediterranean Sea (Bozzano et al., 2013; Pensieri et al., 2016).

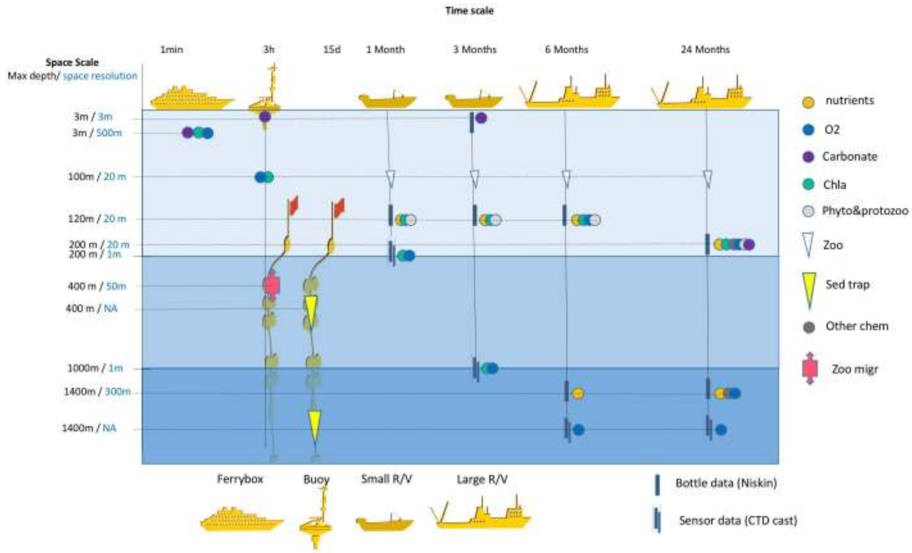

FIGURE 6 | Time and space resolution of data acquisition by the different platforms of the POSEIDON observatory (Argos, Gliders excluded). Space resolution is vertical except for Ferrybox. Carbonate: pH or CT&AT, Other chem: other chemical parameters, Sed trap: sediment trap, Phyto & protozoo: phytoplankton and protozoans; Zoo: metazoans, Zoo migr: ADCP backscatter data for zooplankton-micronekton migration [from Petihakis et al. (2018)].

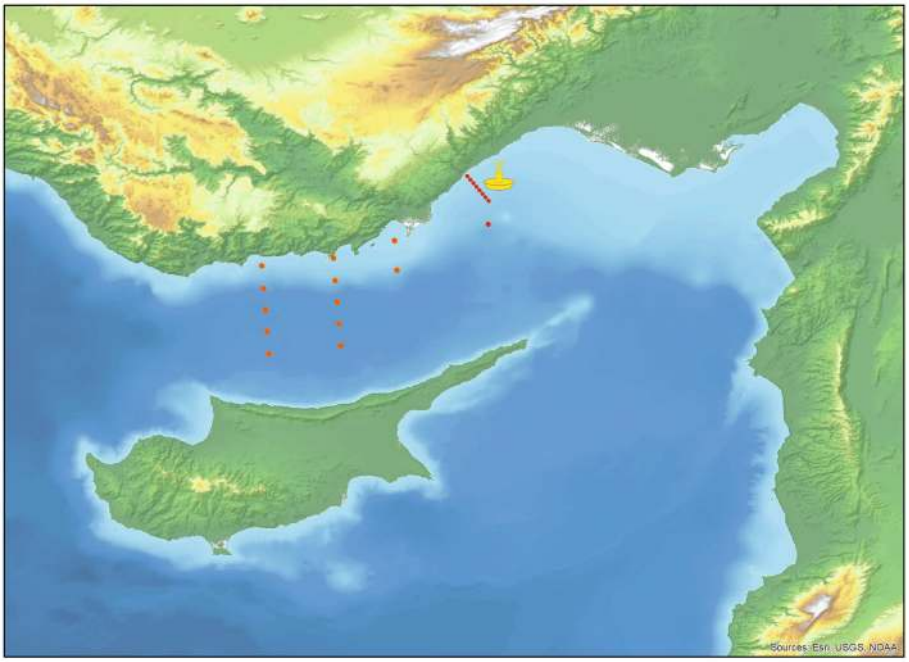

FIGURE 7 | DEKOSIM Erdemli Time Series stations shown in red, the mooring site and seasonal monitoring indicated with orange.

The critical issue for the POSEIDON observatory is its sustainability. The multiparameter, multiplatform observatory approach allows for the participation in various research projects and thus the provision of funds through multiple sources. In addition, the long experience acquired, and the particular conditions of the Eastern Mediterranean, makes the observatory an excellent test bed for new technology.

The POSEIDON system will offer additional products to a wider range of society users, through its expanded NRT data delivery, proxy estimations, hazard mapping, warning systems and higher resolution, in addition to addressing specific scientific questions. For example, deep water ADCP data from the Cretan Sea provided insights into important processes in terms of ecosystem functioning, such as zooplankton migration (Potiris et al., 2018). The observation of the various patterns of vertical migration and of mesopelagic inhabitants, makes possible the investigation of the role of these components in organic carbon sequestration.

DEKOSIM

The Center for Marine Ecosystems and Climate Research (DEKOSIM) is the leading oceanographic research center in Turkey. The center builds upon four decades of experience from the Middle East Technical University's Institute of Marine Sciences. DEKOSIM provides knowledge transfer tools to assist authorities and other stakeholders to manage routine tasks and evaluate trends.

DEKOSIM activities since 2012 can be grouped into the three sectors of observing systems, model products and policy outputs. Observing activities comprise fixed and mobile observatory development and expedition-based time series high-frequency observations. To initiate a sustainable, more comprehensive and long-term monitoring programme in the north-eastern Mediterranean, DEKOSIM started the Erdemli Time Series (ETS) programme in 2013, which built on the fragmented, semi-regular time series measurements collected since 1997. In ETS, a total of 9 stations between 20 and 500 m depths are monitored monthly for T, S, and DO (**Figure 7**). Further, monthly measurements for biological and chemical essential ocean variables (T, S, DO, Chl, Tur, Par, Secchi disk) are conducted at 4 selected stations at 20, 100, 200, and 500 m depths. In addition, monthly trawl surveys have been carried out since 2007 to investigate and monitor demersal fish stocks. A mooring system that has 7 underwater inductive sensors (T, S, DO) at different levels of the water column and meteorological sensors was deployed on the ETS at 100 m water depth. The data can be acquired daily from the mooring. DEKOSIM also supported Argo deployments in the region and 850 profile data have been acquired from 4 Argo floats in Black Sea and 2 in Mediterranean since 2013 within the DEKOSIM. The DEKOSIM information system provides data storage and quality control facilities, according to Seadatanet procedures. The two major scientific achievements, deriving from the DEKOSIM monitoring, are related to the characterization of a possible formation pathway for the LIW in the northern Cilician Basin and the strong land-sea coupling

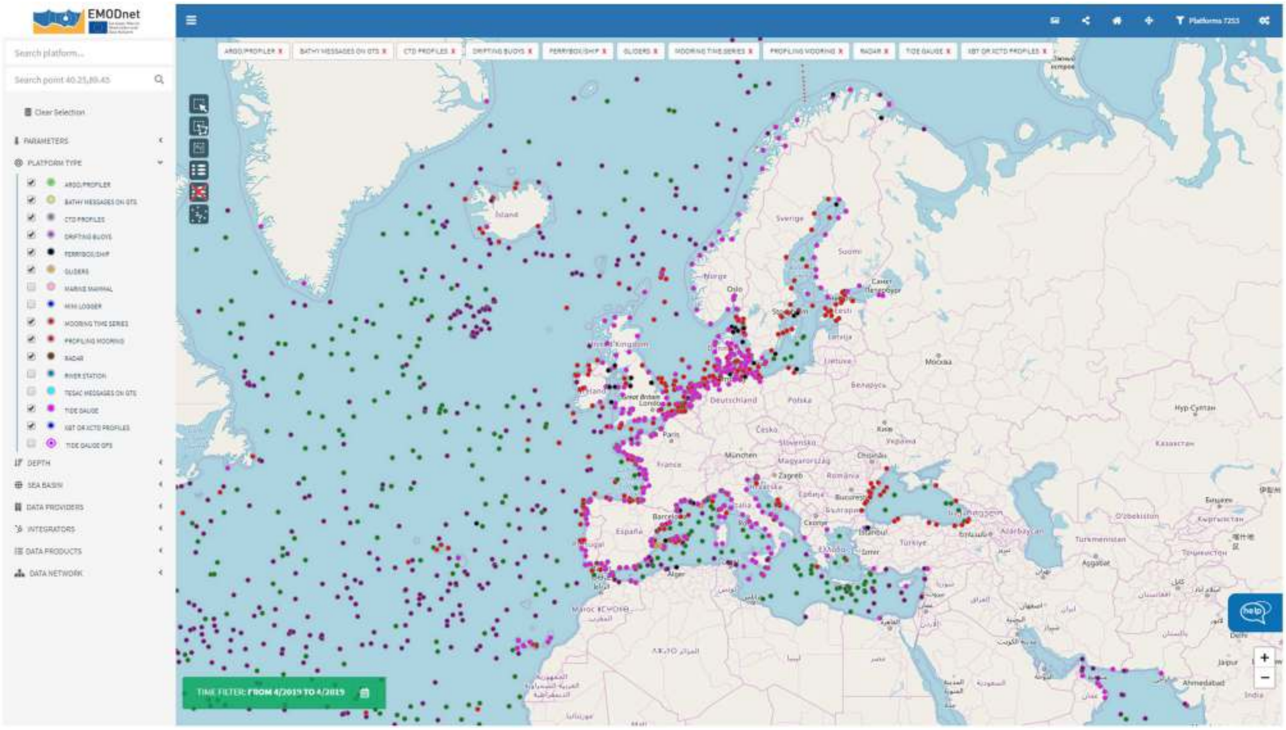

FIGURE 8 | Snapshot of the sampling platforms sending real time data to EMODnet Physics Portal (http://www.emodnet-physics.eu/Map/) as of 1 week in April 2019.

observed in North-eastern Mediterranean and the resultant relatively high productivity.

SELIPS-ISRAMAR

The South Eastern Levantine Israeli Prediction System (SELIPS) and the Israel Marine Data Center (ISRAMAR, https://isramar.ocean.org.il) were established 20 years ago at the Israel Oceanographic & Limnological Research (IOLR) Center as a research and monitoring infrastructure. They provide scientific data and knowledge and effective management and protection programmes for the marine environment. Both systems were integrated in several national and international/EU initiatives dedicated to operational oceanography and data archiving.

The SELIPS-ISRAMAR contain various forecasting and observational platforms operating at different scales. Since 2002 bi-annual monitoring cruises have been conducted in the SE Levantine basin along transects from 20 to 1,700 m water depths, and 70 km offshore by the R/V Shikmona until 2016 and further by the R/V Bat Galim. Profiles of pressure, temperature, salinity, dissolved oxygen and fluorescence, along with water samples for alkalinity, dissolved oxygen, nutrients, chlorophyll-a (Chl-a), picophytoplankton and bacterial abundances, primary and bacterial production and bacterial diversity are collected at eight permanent stations.

IOLR established a modern near real-time meteo-marine monitoring station in 1992, 2.3 km offshore at the Hadera coal terminal (central Israel), which is identified as GLOSS station #80 (https://isramar.ocean.org.il/isramar2009/Hadera/). The parameters monitored are sea level, waves, seawater temperature, salinity, dissolved oxygen, turbidity, fluorescence, and atmospheric pressure. A similar monitoring station was established 2.3 km offshore of Ashqelon (south Israel) in 2012.

IOLR has operated the Deep Levantine Marine Station (DeepLev) since November 2016, which is the first deep-moored research and monitoring station in the SE Levantine Basin (LB), located 50 km offshore of Haifa (Israel) at a water depth of 1,500 m. It carries an array of instruments, including various current meters (ADCPs), CTDs, sediment traps, fluorometers and turbidity sensors, aiming to produce a long-term, high-resolution characteristic of the physical, chemical, and biological dynamics of the water column. In addition, IOLR operates ocean gliders for monitoring activities, which conduct bi-annual transects along N-S and E-W at the SE LB.

Finally, since 2001 ISRAMAR has been a repository for oceanographic data (physical, chemical, biological) and acquires, archives and distributes data and information about the marine environment. It also contain a marine barcoding database consisting of DNA-barcode tagging, identification and taxonomy with the purpose of promoting taxonomic knowledge for marine biodiversity (https://isramar.ocean.org.il/IsraelBarcoding). Since 2007, a synoptic database of ocean color parameters offshore of Israel using Earth Observation has been generated by SISCAL (Satellite-based Information System on Coastal Areas and Lakes, operated by IOLR). These include maps of the Sea Surface Temperature (SST), Chlorophyll-a concentration, Total Suspended Matter and Secchi depth, obtained from operational ocean observing satellites.

The SELIPS-ISRAMAR has acquired 30 years' worth of hydrographic observations, showing that the south-eastern Mediterranean Sea is getting saltier and warmer at rates in agreement or higher than the IPCC 2014 high end prediction (Ozer et al., 2017). In addition, Lagrangian analysis of circulation patterns has provided a better understanding of shelf-deep sea interactions and filament formation (Efrati et al., 2013).

PORTUS (Puertos del Estado System)

The observational component of the Portus system in the Mediterranean Sea consists of 7 deep water buoys (able to measure currents, SST, salinity, wind, atmospheric pressure, air temperature and waves), 6 coastal buoys (waves and SST), 2 HF radar systems (Catalan coast and straits of Gibraltar) and 16 tide gauges. This comprehensive observing system is fully integrated into the modeling component of the Portus (see the section below) and serves data for multiple socio-economic sectors with the main customer being the Spanish Port system, via the SAMOA service (see section Downstream Services in Response to Societal Challenges and Stakeholders). Real-time data access is provided via Portus web site[7].

MAOS (Mobile Autonomous Oceanographic Systems)

The MAOS[8] is an Italian infrastructure using mobile autonomous instruments, such as gliders, floats and drifters, to measure marine properties with its main focus on the Mediterranean Sea. It contributes substantially to the Argo fleet in the Mediterranean with the deployment of about 20 floats annually since 2012. In addition to standard Argo floats, MAOS has operated several floats equipped with biogeochemical sensors and the first floats profiling as deep as 4,000 m in the Mediterranean. MAOS is also coordinating the deployment of all the Argo floats in the Mediterranean and is responsible for the delayed mode quality control of their data, in the framework of MedArgo (Poulain et al., 2007), the Argo Regional Center for the Mediterranean. Among various applications, Argo float data have been used to study convection and dense water formation in the Adriatic Sea (see for instance Bensi et al., 2013).

MAOS also regularly operates several types of surface drifters to monitor the surface currents and temperature, and maintains a historical drifter database (Menna et al., 2018). It uses four gliders to measure water mass properties in the Mediterranean, with the main focus on the Italian seas and the Levantine Basin. MAOS also runs a glider endurance line across the southern Adriatic Sea to monitor dense water formation processes.

RITMARE

The Italian RITMARE Flagship Programme, which began in 2012, aimed to implement the RITMARE Ocean Observing System for the Italian seas by building on existing infrastructures, to help implement national and European environmental regulations and to contribute to the future European Ocean Observing System. The network now integrates different platforms, i.e., coastal buoys, oceanographic towers, coastal, open ocean and cabled moorings, HF and X-band radars, gliders,

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[7] http://portus.puertos.es

[8] http://maos.inogs.it

satellite products and modeling components. The ongoing efforts are aimed at increasing the number of active platforms, to align the sensors, improve the near real time QA/QC, and to develop new remote sensing algorithms and products.

The system presently consists of 17 fixed point observatories, 5 gliders, a variable number of operating drifters and floats, 3 HF radars, and several operational models. In addition, repeated transects on board R/Vs are conducted in all Italian Seas. Since 2015 a 6-monthly glider transect has been conducted between Sardinia and the Balearic Islands, in cooperation with SOCIB (see **Figure 4**).

The different components of the sustained RITMARE Observing System allow for the description of the carbonate system in coastal and offshore areas (Cantoni et al., 2012, 2016), and the climatology and long term trends of wind waves (Pomaro et al., 2017), to gain insights into dense water formation and dense shelf water cascading processes (Langone et al., 2016; Schroeder et al., 2016), and to detect how climate change induces rapid responses in a marginal sea such as the Mediterranean (Schroeder et al., 2017).

IEOOS

The Spanish institute of Oceanography (IEO) maintains a historical ocean observing system around the Iberian Peninsula, and the Canary and the Balearic Islands, known as IEOOS (Tel et al., 2016). This system provides quality-controlled data from a wide network of tide gauges, hydrographic monitoring sections, permanent moorings, and underway monitoring and is a key contribution the ARGO international programme. Data and metadata following international standards are incorporated into the IEO data archive, linked to the Sea-DataNet network, and thus made accessible.

The RADMED monitoring programme (Lopez-Jurado et al., 2015) is a key element of IEOOS, and has systematically collected hydrographic sections from Barcelona to the Alborán Sea and around the Balearic Islands for over 20 years. This sustained effort has enabled the characterization of the seasonal and interannual variability, the effects of winter convective processes, the presence of water masses, mesoscale structures, transport and exchange between basins, cycles, trends and possible climate changes to be established, in addition to environmental and ecological studies of species (Balbin et al., 2014; García-Martínez et al., 2018). RADMED data have been also used to update temperature and salinity mean values and trends in the Western Mediterranean (Vargas-Yañez et al., 2017). Additionally, the data has been used to characterize spatial and temporal long-term patterns of phyto and zooplankton in the Western Mediterranean (García-Martínez et al., 2019).

Forecasting Systems

The present European leadership in operational oceanography and ocean forecasting has its origin in the coordinated efforts in the Mediterranean that started in the early 1990s, due to EuroGOOS (Pinardi and Flemming, 1998) and the associated EU funded projects (Pinardi and Coppini, 2010), which are the origin of the present CMEMS Med-MFC discussed below.

CMEMS

The CMEMS systems in the Mediterranean are strongly connected to MONGOOS. The Mediterranean Monitoring and Forecasting Center (Med-MFC) is one of the regional production centers of CMEMS. Med-MFC operatively manages a suite of numerical model systems that provide analyses and forecasts of physical and biogeochemical variables for the Mediterranean Sea, with a horizontal resolution of 1/24° (about 3.5 km). The physical component of Med-MFC is provided by a coupled hydrodynamic-wave modeling system (Clementi et al., 2017), assimilating temperature and salinity vertical profiles, and satellite Sea Level Anomaly (Dobricic and Pinardi, 2008). It operationally provides daily updates of 10-day forecasts and weekly updates of analyses. Products include: 3D Temperature, Salinity, Currents; 2D Sea Surface Height, Mixed Layer Depth, Bottom Temperature, Stokes Drift, and Wavenumber.

The biogeochemical component of Med-MFC is forced by outputs provided by the physical component and assimilates the surface chlorophyll concentration measured from satellites. Products include 3D daily fields of Chlorophyll, Nitrate (NO_3), Phosphate (PO_4), Net Primary Production, Phytoplankton Biomass, Dissolved Oxygen, CO_2 partial pressure, and Seawater Acidity (pH).

The wave component of Med MFC is based on a high resolution (1/24°) operational wave forecasting system that provides on a daily basis 1-day hourly hindcasts and 5-days hourly forecasts of the wave environment in the Mediterranean Sea. The 17 available wave products include significant wave height, wind and primary/secondary swell significant wave height, periods, direction, and Stokes Drift velocity.

The CMEMS products support major scientific research and applications, including the evaluation of the sea level trend dynamics (Pinardi et al., 2014), the overturning circulation in the Mediterranean Sea (Verri et al., 2017; Pinardi et al., 2019), oil spill hazard mapping (Liubartseva et al., 2015) and an oil spill emergency response decision support system (Zodiatis et al., 2016a). Multi-year products (both reanalysis and hindcasts) at daily/monthly frequency are also regularly updated once per year and they cover by now the past 30 years. All operational products are made available through the CMEMS service delivery system[9].

SOCIB

The Modeling and Forecasting Facility at SOCIB has successfully developed and implemented three prediction systems which are now run and evaluated on an operational daily basis. These are: the operational regional circulation model nested to CMEMS Med-MFC (Juza et al., 2016; Mourre et al., 2018), the meteo-tsunami pre-operational forecasting system for Ciutadella harbor (Renault et al., 2011; Licer et al., 2017) and the wave forecasting around the Balearic Islands. Research is also conducted to continuously improve and extend the capacity of these systems. The most significant recent advances include a new characterization of the dynamics of ocean eddies in the Algerian basin (Escudier et al., 2016a) and the analysis of multi-year high-resolution numerical simulations to investigate fish

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[9] http://marine.copernicus.eu/services-portfolio/access-to-products/

larvae dispersion (Calò et al., 2018) or simulate high-resolution observations potentially obtained from future satellites such as SWOT (Gómez-Navarro et al., 2018) and the application of machine learning techniques for the interpolation of simulated observations of satellite altimetry (Fablet et al., 2018).

Significant advances have been also achieved on the understanding and simulation of physical-biogeochemical processes, for example on the combined effects of the Atlantic Water inflow at Gibraltar and the associated eastward jet and winds over the phytoplankton distribution in the Alborán Sea (Oguz et al., 2016, 2017), and on the integration of multiplatform observations and high-resolution modeling through data assimilation (Pascual et al., 2017; Hernandez-Lasheras and Mourre, 2018). These results have implications in terms of operational response to emergencies, sustainable management of the marine environment and ecosystems health, and climate.

POSEIDON

Forecasting tools are centrally placed in the POSEIDON system, with a number of state-of-the-art weather, wind waves, ocean circulation and marine ecosystem numerical models, initialization and data assimilation schemes providing 5-days ahead information on daily basis regarding the atmospheric (Papadopoulos et al., 2002), sea state (Korres et al., 2011), and hydrodynamic conditions (Korres et al., 2010) in the Aegean/Ionian Seas and in the Mediterranean, in addition to the ecosystem functioning of the whole basin. In terms of general calibration, validation activities are applied to the operational models as data from the observatory are used in conjunction with experiments (e.g., mesocosms) for the analysis and modeling of specific processes (e.g. Tsiaras et al., 2017) and assimilation algorithms of sea color data are tested and validated in biogeochemical models (Kalaroni et al., 2016).

CYCOFOS

The Cyprus coastal ocean forecasting system, known as CYCOFOS, has been providing operational hydrodynamics and sea state forecasts in the Eastern Mediterranean since early 2002. Recently, it has been improved with the implementation of a new hydrodynamic, wave and atmospheric modeling system with the objective of targeting larger and higher resolution domains, at regional and sub-regional scales (Zodiatis et al., 2016b). For the new CYCOFOS hydrodynamic modeling systems a novel parallel version of the Princeton Ocean Model has been developed and implemented with a 2 km resolution over the entire Eastern Mediterranean and in the Levantine Basin with a resolution of ∼600 m. Both models are nested in the CMEMS Med-MFC. The Weather Research and Forecasting atmospheric model (WRF) has been implemented in the same domain as the SKIRON atmospheric system[10] (Kallos et al., 1997; Papadopoulos et al., 2002), to provide the backup forcing for the CYCOFOS new modeling systems.

All the CYCOFOS modeling systems received an extended cal/val against Argo profiles, satellite SST time series, *in-situ* wave time series and METAR observations (Zodiatis et al., 2018). The CYCOFOS modeling system provides a higher-resolution quality-controlled forecasting data fit for the needs of end users in the fields of maritime safety and oil spill predictions, particularly in view of the recent exploration and exploitation of the hydrocarbons in the Eastern Mediterranean Levantine Basin. Over the past 10 years, the majority of *in-situ* observations around Cyprus have been collected from two ocean gliders, which have been shown to improve the operational forecasting skill of CYCOFOS at scales from 10 to 50 km, most notably in the region of the Cyprus Eddy (Hayes et al., 2019).

SANIFS

The southern Adriatic Sea and Northern Ionian Forecasting System (SANIFS, Federico et al., 2017) is an unstructured grid limited area forecasting system downscaling the CMEMS Med-MFC forecasts up to 10 m along the coasts and inside the harbors. SANIFS is based on a 3D finite element hydrodynamics model (Umgiesser et al., 2004) and it considers 91 vertical levels with a 2 m resolution to a 20 m depth, progressively decreasing the resolution near the bottom. Tidal forcing is applied to the lateral boundaries of the model so that the forecasts can be used for several coastal applications such as coastal erosion, inundation forecasts, and marine pollutants dispersal hazard mapping. The model is nested to CMEMS and forced with ECMWF products with a 6 h frequency and a ∼12 km horizontal resolution. The results are available at the SANIFS site[11].

PORTUS

The Portus forecasting component operates both at the regional scale, with sea level and wave forecasts covering the whole Mediterranean basin, and at the port and coastal scale, with forecasts of circulation (nested into CMEMS models) and waves. At the regional scale, the sea level forecast is provided by a 2D barotropic model covering the whole basin, which has been recently complemented by a multi-model Bayesian model average ensemble based on Copernicus forecasts. The wave forecast is based on the using of WAM forced with Spanish Met Office winds. At the coastal and port scale, multiple models are used to provide high resolution services for ports and coastal areas (see description of SAMOA at section Puertos del Estado Downstream Services).

CAPEMALTA

CapeMalta is the ocean forecasting system for the Maltese Islands. The ROSARIO Malta Shelf forecasting system[12] provides routine online thermo-hydrodynamic predictions for the extended area around the Maltese Islands up to the southern Sicilian coast. The system operates through the use of an eddy-resolving numerical model with two distinct spatial resolutions of 1/64o and 1/96o (about 1 Km) with 1-h and 3-h averaged color maps and animations of temperature, salinity and velocity fields at the sea surface and at selected depths, and a forecast horizon of 4 days. The MARIA Malta Atmospheric and Wave forecasting systems consist of an operational chain of meteo-marine models with downscaling to high resolution sub-domains for the region

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[10] http://forecast.uoa.gr

[11] http://sanifs.cmcc.it/

[12] http://www.capemalta.net/MFSTEP/results.html

north of 34° latitude in the Sicilian Channel and comprising the Maltese Islands.

The wave forecast uses the 3rd generation WAM Cycle 4 spectral wave model. The model is forced by surface wind and runs daily to produce a 72-h forecast on a high-resolution grid (1/8°) over the Central Mediterranean. More refined wave conditions in the coastal and near-shore areas are predicted at high spatial resolution by using the SWAN model over the domain defined by 14.040–14.700° longitude and 35.665–36.206° latitude, and a spatial resolution of 0.002°, generating output fields every 3 h.

Data Assembly Systems

CMEMS Thematic Assembly Centers

The CMEMS data assembly structure is organized around *in-situ* and satellite Thematic Assembly Centers.

The CMEMS *in situ* Thematic Assembly Center (*in situ* TAC) (Petit de la Villeon et al., 2018; Le Traon et al., 2019) integrates near real-time *in-situ* observational data. These data are collected from the European members and complemented by the observations collected through the GTS in the area. The details of the physical parameters and data management procedures can be found in Copernicus Marine *in situ* TAC Data Management Team (2018). The data are quality controlled using automated procedures and the database is updated continuously, providing observations within 24–48 h from acquisition. CMEMS Mediterranean *in-situ* TAC works in coordination with MONGOOS (section MONGOOS Collaborative Framework) and EMODnet to access almost all the real-time data collected in the basin by the European Members States.

The CMEMS remote-satellites Thematic Assembly Centers (Sea Ice TAC, Surface Wind TAC, Sea Level TAC, Ocean Color TAC, Sea Surface Temperature TAC, Wave TAC, Multi Observations TAC) make available several data products from all functioning satellites for altimetry, infrared and visible multi-band radiometers every day. The satellite data are also re-processed every week giving the optimal estimates of the atmospherically corrected sea level.

EMODnet

EMODnet is a data assembly initiative supported by the European Directorate General MARE, which collects, transforms and makes available in a consistent manner several thematic data sets related to the marine environment. These are bathymetry, geology, seabed habitats, chemistry, biology, physics, and human activities. They span a larger set of EOVs, which are required in the fulfillment of the UN SDGs. They are complementary to the CMEMS *in situ* TAC because they are mainly concerned with historical data and making accessible the past and present data in a common, interoperable format. EMODnet has had, from the beginning, a wider scope of application than CMEMS, thus making data available for reuse to the overall European and International community. EMODnet relies strongly on *in-situ* TAC data collection.

The EMODnet Physics Web GIS system allows the monitoring of the working platforms in the Mediterranean Sea on the basis of different time intervals and thus it is a very useful tool for planning new deployments of measuring platforms (see **Figure 8**).

The Mediterranean Sea is an area of EMODnet intensive data assembly in all thematic areas, and the EMODnet Checkpoint initiative has assessed the data adequacy of the basin scale monitoring system[13].

SeaDataCloud

SeaDataCloud[14] is a European-wide infrastructure for the development of standardized access to European marine data from more than 100 data centers. Its aim is to preserve and make re-useable marine observations ranging from ocean physics to chemistry and biology. It uses the strategy and standards of the Unesco IODE programme.

The work of SeaDataCloud is the basis of the EMODnet Portals, and develops data management standards, vocabulary, and quality control procedures, and encourages best practices throughout the marine data management sector. SeaDataCloud is the most recent outcome of 15 years' continuous development, and it will use cloud and high-performance computing technology for better performance. SeaDatacloud in the Mediterranean connects the National Oceanographic Data Centers (NODC) and produces high quality climatologies using historical data from 1900 to the present.

Regional Data Management Systems

The Mediterranean observing systems described in section Multi-Platform Observing Systems all have dedicated data management infrastructures. Here we only present three of the main and permanent systems in the Eastern and the Western Mediterranean. MOOSE relies on the national data management centers for real-time and delayed-mode data (SEDOO, SISMER). Data sets are organized by platform and DOIs are attributed to each platform deployment. Delayed mode quality controls are carried out by MOOSE while real-time data are quality controlled by standard procedures at Coriolis. These data centers allow for the dissemination of the data to the public in internally approved formats. The POSEIDON Data Center, as the regional data collection unit of the CMEMS, ensures that the recorded data is compatible with other large European data infrastructures (EMODnet, CMEMS and SeaDataNet). Data can be visualized through the POSEIDON website (fixed platforms, Ferrybox) and the MONGOOS data portal[15], while the data are freely available to the public, the stakeholders and the scientific community. The SOCIB Data Center also manages the full data life cycle: acquisition, assembly and processing (including quality control), archiving, preservation and dissemination. A variety of systems have been developed to achieve these goals. For example: a glider toolbox (Troupin et al., 2016) for data processing and assembly is available through GitHub and is being used for processing glider data internationally. A new Data Catalog API (Fernández et al., 2018) allows discovering the SOCIB data catalog and retrieving

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[13] http://www.emodnet-mediterranean.eu/

[14] https://www.seadatanet.org/

[15] http://www.mongoos.eu/data-center, all platforms except sediment traps and ADCP.

its data directly. DOIs are also attributed by platforms and/or for dedicated intensive experiments (Cotroneo et al., 2019).

MONGOOS COLLABORATIVE FRAMEWORK

The Mediterranean Sea basic systems/services were first implemented by EuroGOOS in the late 1990s (Pinardi and Flemming, 1998; Pinardi and Woods, 2002). More recently the GOOS Regional Alliance (GRA) for the Mediterranean Sea was established as the Mediterranean Operational Network for the Global Ocean Observing System (MONGOOS), which also serves also as a ROOS for EuroGOOS. MONGOOS was established in 2012, merging the previous two groups, MOON and MedGOOS, to further develop operational oceanography in the Mediterranean Sea.

MONGOOS has identified the relevant regional stakeholders and reference users of the MONGOOS basic services and products, and memorandums of agreements have been established with them to formalize the work. They are available from the documents section of the MONGOOS web site[16].

MONGOOS Coordinated Observational Capacities

A catalog of MONGOOS monitoring platforms is offered via the MONGOOS Data Center, integrated into the MONGOOS web page. Access to real time data from most of the MONGOOS monitoring platforms is provided through the CMEMS *in-situ* TAC and the EMODnet Physics Portal. Although there are evident gaps (e.g., no tide gauges are reported in Greece), it constitutes one of the most comprehensive catalogs of available oceanographic measurements in the region. **Figure 9** shows the distribution of wave, sea level, SST, and salinity measuring platforms.

There are 58 buoys capable of measuring waves, most of which are directional (**Figure 9A**). Coverage is more complete in the Western basin, and there is an almost total absence along the African coast, with the exception of Ceuta and Melilla stations. A total of 100 sea level stations are reported (**Figure 9B**). There is a significant gap in Eastern Europe, due to lack of coordination with the community. A total of 37 current meters are operational across the region (**Figure 9C**). Water temperature is the most frequently and regularly measured variable, with 113 stations (**Figure 9D**). Fifty salinity stations are reported.

Several buoys and towers can measure atmospheric variables over the sea and the catalog contains information of 80 Meteorological stations capable of measuring air pressure, temperature and wind. A total of 11 HF radar systems (with an overall of 32 HF radial sites), accounting for 52% of the European HFR network (Rubio et al., 2017), have been or are currently in operation in the area (**Figure 10A**). More information can be found at http://www.mongoos.eu/hf-radars. Additionally, HF radar datasets can also be found in the new product (INSITU_GLO_UV_NRT_OBSERVATIONS_013_048) for near real-time surface current data in the CMEMS Catalog (V5), included in the recently updated CMEMS service release.

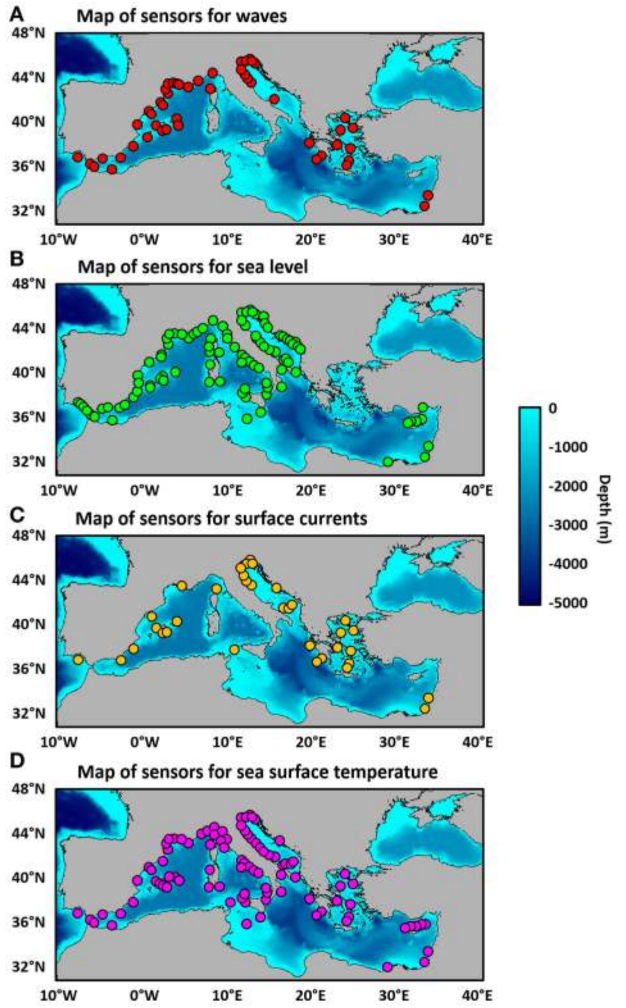

FIGURE 9 | Map of sensors deployed in the Mediterranean Sea for monitoring purposes (as in 2017): **(A)** waves, **(B)** sea level, **(C)** surface currents, and **(D)** sea surface temperature.

Since the early 2010s over 60 Argo floats have been established in the Mediterranean basin, with 78 instruments in June 2019 (**Figure 10B**) and 7 Glider facilities (**Figure 10C**). More information can be found at the Mongoos web site[17].

In summary, for some variables and in certain regions, the monitoring system is satisfactory. For example, the number of tide gauges on the western European Mediterranean coast is sufficient for most of the applications (study of sea level trends, storm surge monitoring, etc.). Similar situations can be found for wave buoys. Nevertheless, the gaps and limitations of the monitoring system are clear and often significant. First, there is a marked North-South imbalance, with the southern shores not coordinated with the northern basin monitoring system.

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[16] http://www.mongoos.eu/

[17] http://www.mongoos.eu/profilers-and-drifters-med-argo

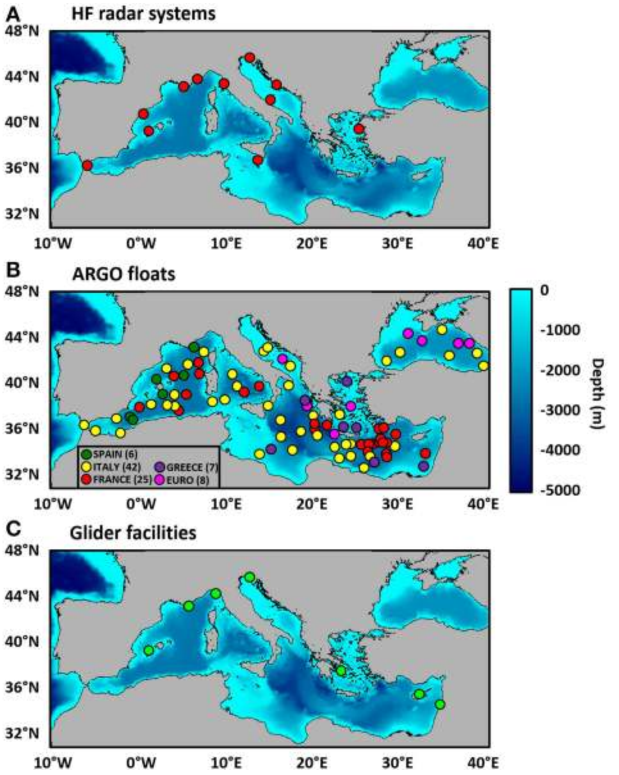

FIGURE 10 | Map of sensors deployed in the Mediterranean Sea for monitoring purposes: **(A)** High Frequency radars, **(B)** Argo Floats as in 2018, and **(C)** Gliders.

Even on the European coasts, there is an obvious unequal distribution of sensors due to the lack of global planning. Other variables like currents are clearly under-sampled throughout the region, and the same applies for salinity and water temperature, although for these variables data from gliders and Argo serve to mitigate the situation. In any case, due to the size of the relevant dynamical and mesoscale structures in the region, the limited number of platforms is insufficient to properly contribute to data assimilation in numerical models.

MONGOOS Coordinated Forecasting Systems

A catalog of regional to subregional modeling and forecasting systems outside CMEMS is provided through the MONGOOS showcase tool. The tool directly links to the services operated by institutions across the Mediterranean Sea. From the analysis of the data available on the tool, the following description of the modeling situation in the region is obtained.

There are 33 recorded, operational wave models in the Mediterranean Sea. Some of them cover the whole basin and others are nested in the CMEMS wave model or others, to provide solutions to harbors or coastal areas. Most of the large-scale implementations are based on the WAM and Wave Watch models, while the coastal applications use mostly SWAM. The atmospheric forcing used by the wave models also differs, including ECMWF, HIRLAM, COSMO and WRF atmospheric limited area forecasting models. The Eastern and Western sub-basins have a similar number of models and there is an absence of high-resolution nested application on the African Coast.

In terms of circulation and hydrography, most of the models are nested into the CMEMS Med-MFC. Nested forecasting systems use several types of models, including the Princeton Ocean Model (Blumberg and Mellor, 1987), ROMS (Regional Ocean Modeling System, Shchepetkin and McWilliams, 2005), NEMO (Nucleus European Model of the Ocean, Madec, 2016) and SHYFEM (Ferrarin et al., 2019). These limited area models usually do not assimilate observations, which are instead assimilated in the CMEMS model.

There is good coverage in both sub-basins, with a typical forecasting horizon of between 5 to 10 days. The common resolution is 1 or 2 km, but is as low as 200 m in the case of the PORTUS model at the Strait of Gibraltar and SANIFS, where resolutions of 10 m are attained inside the harbors. The number of vertical levels is typically between 20 and 100 using various coordinate systems. Almost all the operational sub-regional models are executed once per day.

Some of the models use atmospheric pressure forcing, which is fundamental for sea level (storm surge) short-term forecasts. A few systems specialize in this variable and phenomenon, working in 2D barotropic mode. In this category it is worth to mention Kassandra system (Ferrarin et al., 2013) and the Nivmar service (Alvarez Fanjul et al., 2001), part of the PORTUS system.

In terms of quality and quantity of the operational systems, the Mediterranean area is reasonably well-covered, but few comparison exercises to understand the gaps and performance limitations are conducted and should be increased in the future. Also, by taking advantage of the many models present, ensemble multi-model forecasting in some coastal areas could be evaluated.

DOWNSTREAM SERVICES IN RESPONSE TO SOCIETAL CHALLENGES AND STAKEHOLDERS

In this section we present some of the most relevant and most used downstream services developed in response to societal challenges and stakeholders. Operational oceanography currently reaches thousands of users through services addressing societal challenges (e.g., CMEMS), including maritime safety, coastal and marine environment management, climate change assessment, and marine resources management. Freely available products from CMEMS allow the development of specific applications, such as Decision Support Systems (DSS) and services for users and stakeholders.

Oceanographic products from CMEMS and downscaled sub-regional and national products are used, transformed, and provided to users, private companies and stakeholders through adding-value chains (downstreaming), which consider the development of specific solutions, advanced visualization, the use of multi-channel technological platforms and specific models and algorithms.

Several examples of downstream services are given below.

Puertos del Estado Downstream Services

Approximately 85% of total imports and 60% of Spanish exports are channeled through ports, illustrating the vital role they play in the national economy. The ports suffer from the extreme events of the essential physical variables, and particularly wind, waves and sea level. These affect the installations during all phases of a harbor's life, from design to operation. To respond to these complex needs, the SAMOA[18] initiative was born (**Figure 11**), co-funded by Puertos del Estado and the Port Authorities. An integrated system based on CMEMS data has been developed. A total of 10 new high-resolution atmospheric models (1 km resolution, based on Harmonie), 10 wave models (5 m, mild slope model) and 9 circulation models (70 m, ROMS), Sotillo et al. (2019) have been developed and operationally implemented. In terms of instrumentation, SAMOA improved the already existing large network of Puertos del Estado with 13 new meteorological stations and 3 Global Navigation Satellite Systems (GNSSs) associated to the tide gauges. Twenty five ports from 18 Port Authorities will benefit from these new modeling and monitoring developments.

To properly exploit all SAMOA products a dedicated a tool has been developed for the Port Authorities and is currently implemented in 25 ports. This tool, the Environmental Panel Dashboard is based on a web interface[19] and provides easy access to all the information generated by the SAMOA systems, both in real time and in forecast mode. The user can define thresholds for all spatial points inside the application (model points and measuring stations) that are used to trigger alerts. The CMA is also capable of creating customized PDF reports for each forecast point. Additionally, a user-friendly oil spill model and an atmospheric dispersion model have been developed and implemented into the CMA.

Managers of the ports granted access for the tool and defined the levels of user permissions. For example, some users can access visualization but may not have access to the oil spill model, A growing community of 1,250 port users exploit the CMA tool. SAMOA is being improved through the framework of the new SAMOA 2 project. By 2021, a total of 46 ports will have a version of CMA implemented.

SOCIB Innovation, Products, and Services

In terms of innovation, in 2018 SOCIB developed (Heslop et al., 2019) a sector-focused products and services strategy that allowed identification of 10 key user sectors (groups of users with common data interests and needs) which are important to the region (economically/societal benefit) and already receive data of value from SOCIB (e.g., value to decision-making). The implementation of this strategy is now underway and by the end of 2019 the SOCIB website will include a new searchable product catalog, with detailed information on existing products, and new sector-focused products (e.g., for lifeguards on beaches and for the sustainability of Bluefin tuna). Regional ocean observatories have a key role to play in delivering societal benefits from ocean data and research, and the SOCIB efforts concentrate on the coastal component of a future European Ocean Observing System (EOOS).

The sectors and related end users (in brackets) that are now core to SOCIB products strategy are:

- Marine and coastal research (academia, government policy makers and responsible, NGOs)
- Maritime safety (SAR operators, coastguard, oil spill response managers, maritime emergency managers, navy & national security agency)
- Marine sports (recreational sailing, sports sailing/regattas, surfing, diving)
- Beach and coastal communities (citizens, tourists)
- Coastal protection, coastal risks, planning and governance, **Figure 12** (government environmental managers, lifeguards, beach and coastal planners, energy company managers)
- Ports and Shipping (port managers, port pilots, ferry companies/captains, shipping companies/captains, cruise companies/captains)
- Integrated coastal zone and ocean management (ICOM managers, MPA managers, marine managers, water quality operators)
- Sustainable marine ecosystems (fisheries managers, fisheries scientists, commercial fishermen, recreational fishermen, sustainability managers)
- Sustainability of islands and climatic change (government policy, sustainability managers)
- Education and kids (school kids/teachers, higher education kids/ teachers, society)

As an extension to its scientific and societal research and operational activities, SOCIB also undertakes significant outreach work. The SOCIB Outreach Service promotes ocean literacy and raises awareness on the impact of new ocean observing systems on the advancement of knowledge, science-based management and the preservation of marine and coastal resources. The aim is to bring ocean data and ocean science concepts to all citizens and classrooms. Since 2011, SOCIB has participated in 39 events (science fairs, workshops, national contests, etc.) with 20912 participants, and has produced 44 training resources, and educational material, online games and apps for children and teachers[20]. It has been mentioned 621 times in the media.

OceanLab Services

CMCC (Lecce, Italy) has been developing a series of downstream services since the beginning of 2012, based on the CMEMS analysis and forecast products. They are all digital products/services that add value to the generic data available from CMEMS, and address the requirements of the three main maritime and industrial sectors in the Mediterranean Sea.

The first service is dedicated to tourism and the general public. This is a general-purpose visualization service[21] (Coppini et al.,

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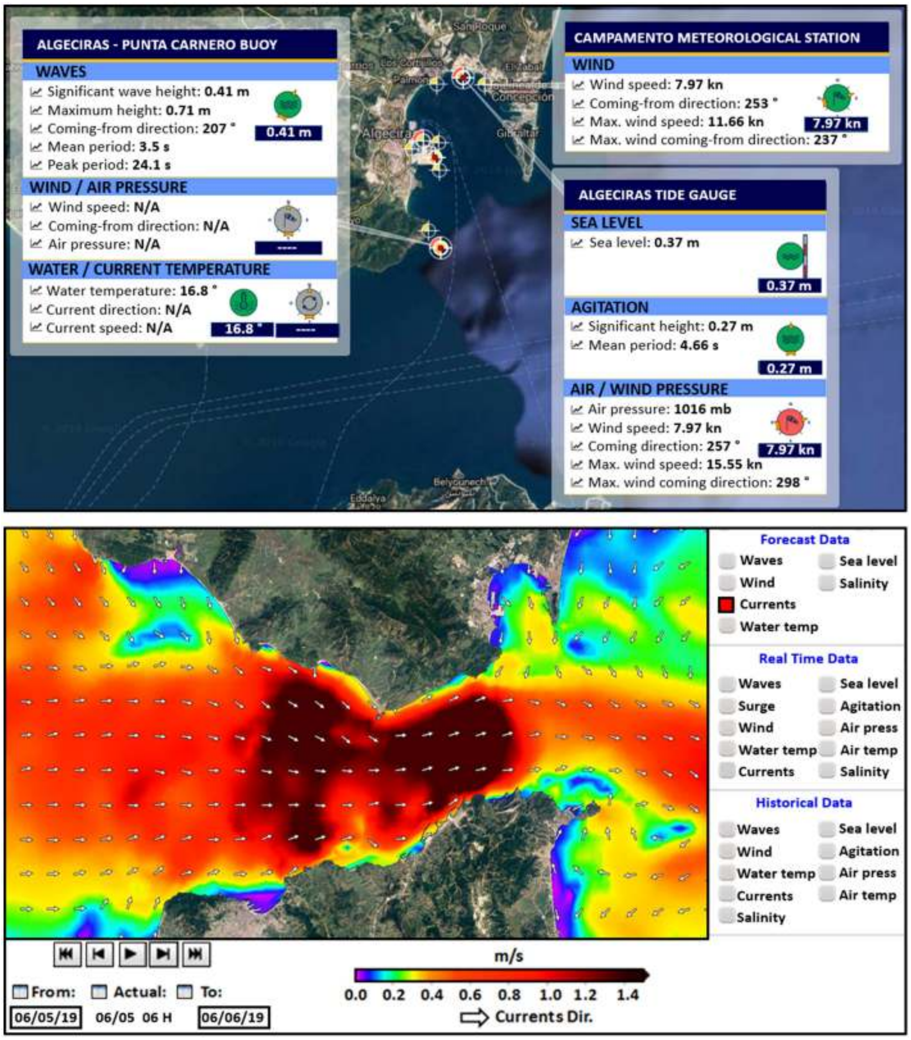
[18] In Spanish: *Sistema de Apoyo Meteorológico y Oceanográfico a las Autoridades portuarias* - System of Meteorological and Oceanographic Support for Port Authorities.

[19] In Spanish *Cuadro de Mandos Ambiental* - http://cma.puertos.es

[20] mainly online at www.socib.es and more specifically at the outreach portal Medclic, www.medclic.es

[21] www.Sea-Conditions.com



ALGECIRAS - PUNTA CARNERO BUOY

WAVES
Significant wave height: **0.41 m**
Maximum height: **0.71 m**
Coming-from direction: **207 °**
Mean period: **3.5 s**
Peak period: **24.1 s**

WIND / AIR PRESSURE
Wind speed: **N/A**
Coming-from direction: **N/A**
Air pressure: **N/A**

WATER / CURRENT TEMPERATURE
Water temperature: **16.8 °**
Current direction: **N/A**
Current speed: **N/A**

CAMPAMENTO METEOROLOGICAL STATION

WIND
Wind speed: **7.97 kn**
Coming-from direction: **253 °**
Max. wind speed: **11.66 kn**
Max. wind coming-from direction: **237 °**

ALGECIRAS TIDE GAUGE

SEA LEVEL
Sea level: **0.37 m**

AGITATION
Significant height: **0.27 m**
Mean period: **4.66 s**

AIR / WIND PRESSURE
Air pressure: **1016 mb**
Wind speed: **7.97 kn**
Coming direction: **257 °**
Max. wind speed: **15.55 kn**
Max. wind coming direction: **298 °**

☐ From: 06/05/19
☐ Actual: 06/05 06 H
☐ To: 06/06/19

FIGURE 11 | User interface of the SAMOA system at Algeciras Port (Strait of Gibraltar). Real time data (upper panel) and circulation model snapshot (lower panel) (https://cma.puertos.es).

2017) that makes available the analyses and forecasts of ocean and atmosphere on several digital platforms. This is a typical situational sea awareness service that helps tourism operators and recreational users to optimize their work and conduct their activities.

The second service is related to oil spill events and the management of emergencies. Updated forecasts and analyses are made available to an oil spill model (MEDSLIK-II[22]) and an advanced GUI (**Figure 13**) allows the users to predict where the oil will be transported and transformed (Liubartseva et al., 2016). This information is crucial for the planning of actions against accidents and remediation activities.

The third service is dedicated to ship routing for middle-sized vessels. It utilizes real time wave forecasts to find the safest and most efficient route (Mannarini et al., 2016). Users can access the service via an advanced GUI (**Figure 14**). VISIR[23], the model powering this service, has recently been extended to also account for surface ocean currents (Mannarini et al., 2018). This includes an assessment of the contribution of waves and currents to the reduction in the carbon footprints of marine voyages (UN SDG13).

Projects Developing Downstream Services

ODYSSEA (Operating a Network of Integrated Observatory Systems in the Mediterranean Sea) is an EU-funded project[24] aimed at developing, operating and demonstrating an interoperable and cost-effective platform that fully integrates networks of observing and forecasting systems across the Mediterranean basin, addressing both the open sea and the coastal zone. ODYSSEA is a system providing downstream

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[22] http://www.medslik-ii.org

[23] www.visir-model.net

[24] http://odysseaplatform.eu

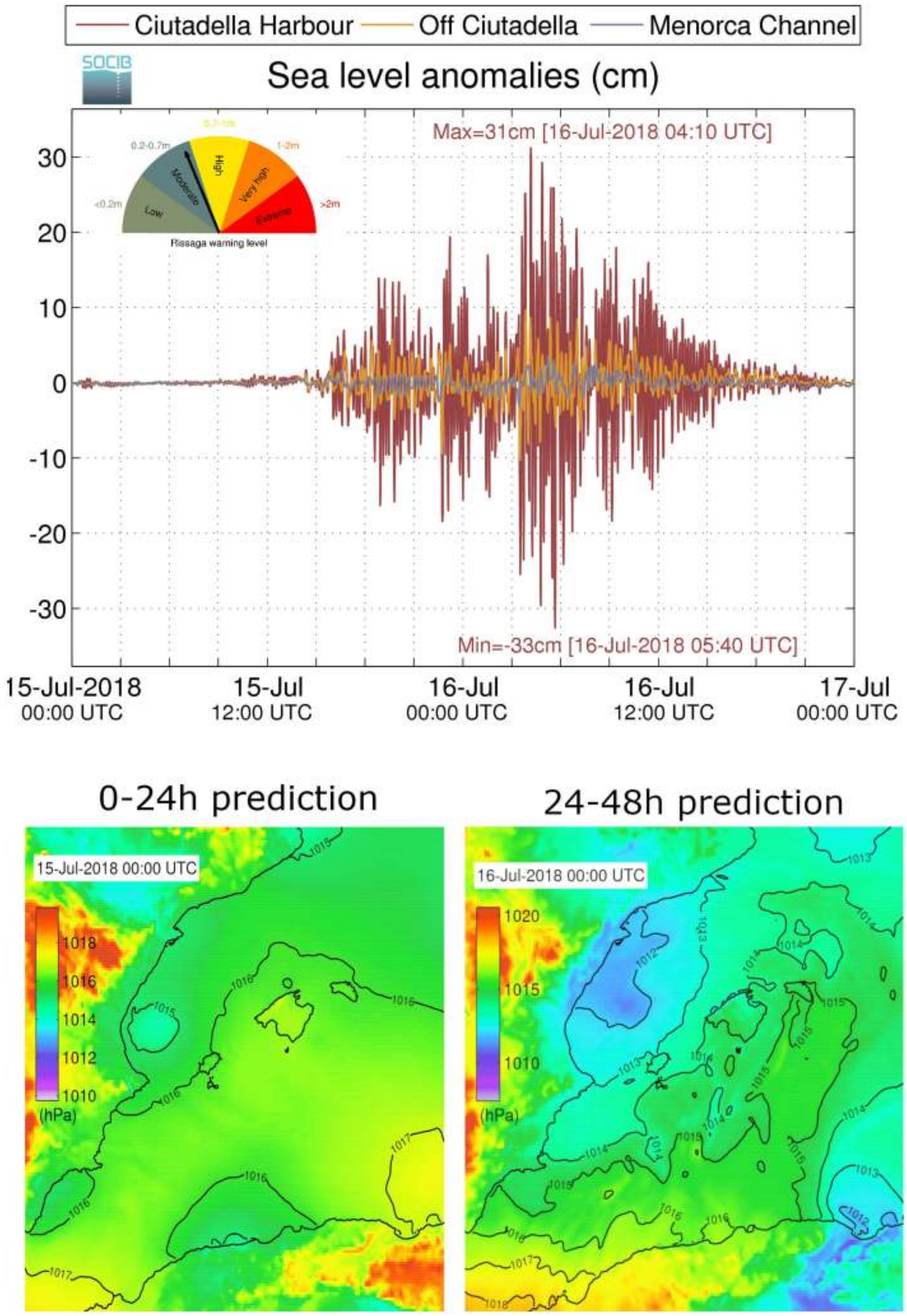
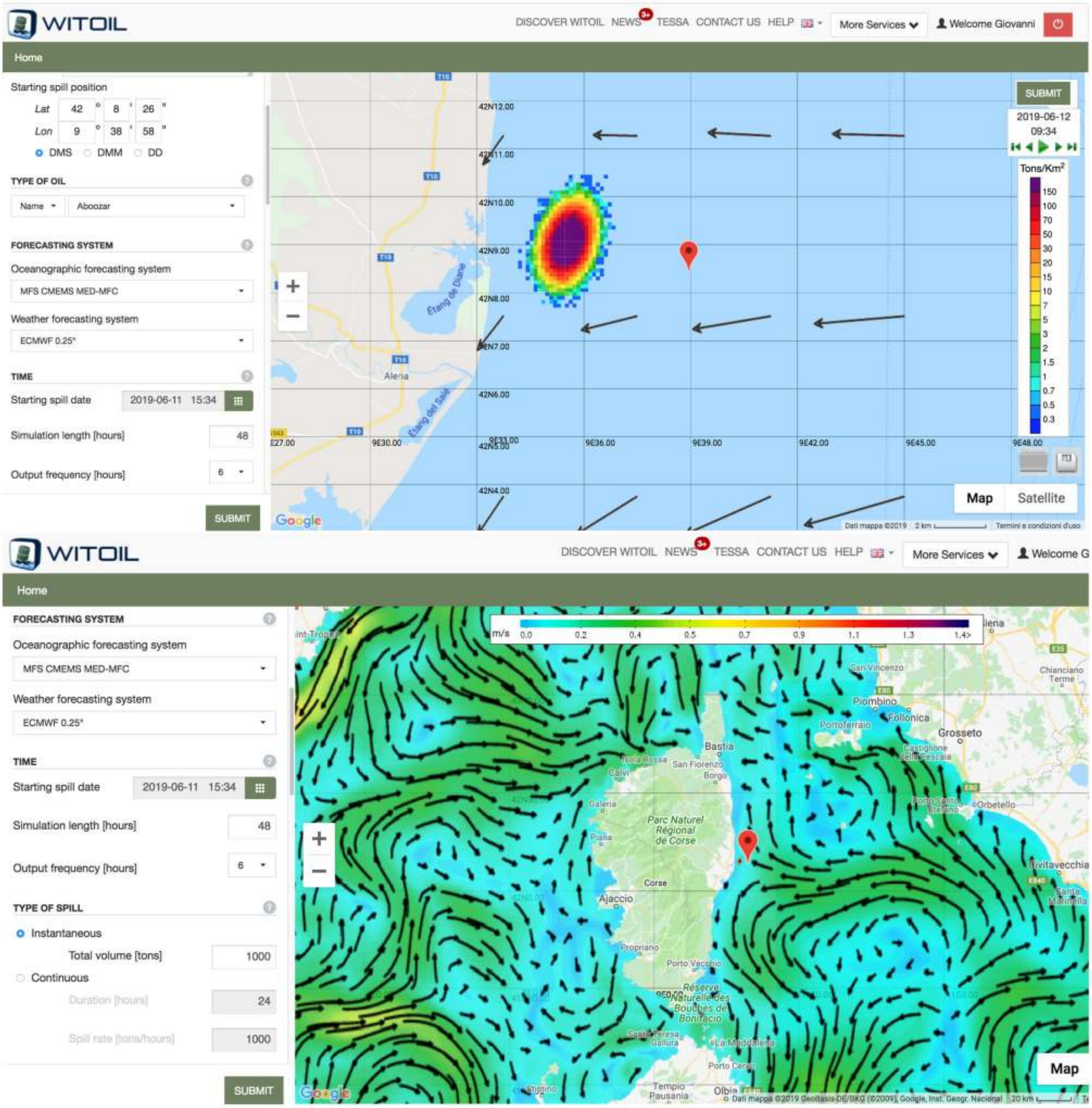


FIGURE 12 | Meteotsunamis BRIFS pre-operational system at SOCIB -www.socib.es- - -showing sea level anomaly at Ciutadella and Menorca channel and the atmospheric pressure distribution at the surface for the July 16 2018 moderate meteotsunami case. www.socib.es/systems/forecast/brifs.

services to bridge the gap between operational oceanography capacities and the need for information on marine conditions from the community of Mediterranean end-users.

The ODYSSEA platform will be operational by 2021 and will provide easy discovery and access to marine data and derived products to a variety of users, to improve knowledge and decision-making capabilities in the Mediterranean. End-users and stakeholders, internal and external to the Consortium, have been involved from day one of the project in the design, development and operation of the platform and in the data collection and operations of observatories.

At the observatories, on-site observations are combined with remote sensing records, and are then assimilated into high-resolution forecasting models. ODYSSEA can upgrade a novel sensor for microplastic monitoring and resize it to be integrated into a glider, a surface and a bottom on-line monitoring platform. These systems will further integrate submerged cameras and passive acoustic monitoring sensors to expand the operational



Starting spill position
Lat 42 ° 8 ' 26 "
Lon 9 ° 38 ' 58 "
● DMS ○ DMM ○ DD

TYPE OF OIL
Name ▾ Aboozar ▾

FORECASTING SYSTEM
Oceanographic forecasting system: MFS CMEMS MED-MFC
Weather forecasting system: ECMWF 0.25°

TIME
Starting spill date: 2019-06-11 15:34
Simulation length [hours]: 48
Output frequency [hours]: 6

SUBMIT

FORECASTING SYSTEM
Oceanographic forecasting system: MFS CMEMS MED-MFC
Weather forecasting system: ECMWF 0.25°

TIME
Starting spill date: 2019-06-11 15:34
Simulation length [hours]: 48
Output frequency [hours]: 6

TYPE OF SPILL
● Instantaneous
Total volume [tons]: 1000
○ Continuous
Duration [hours]: 24
Spill rate [tons/hours]: 1000

SUBMIT

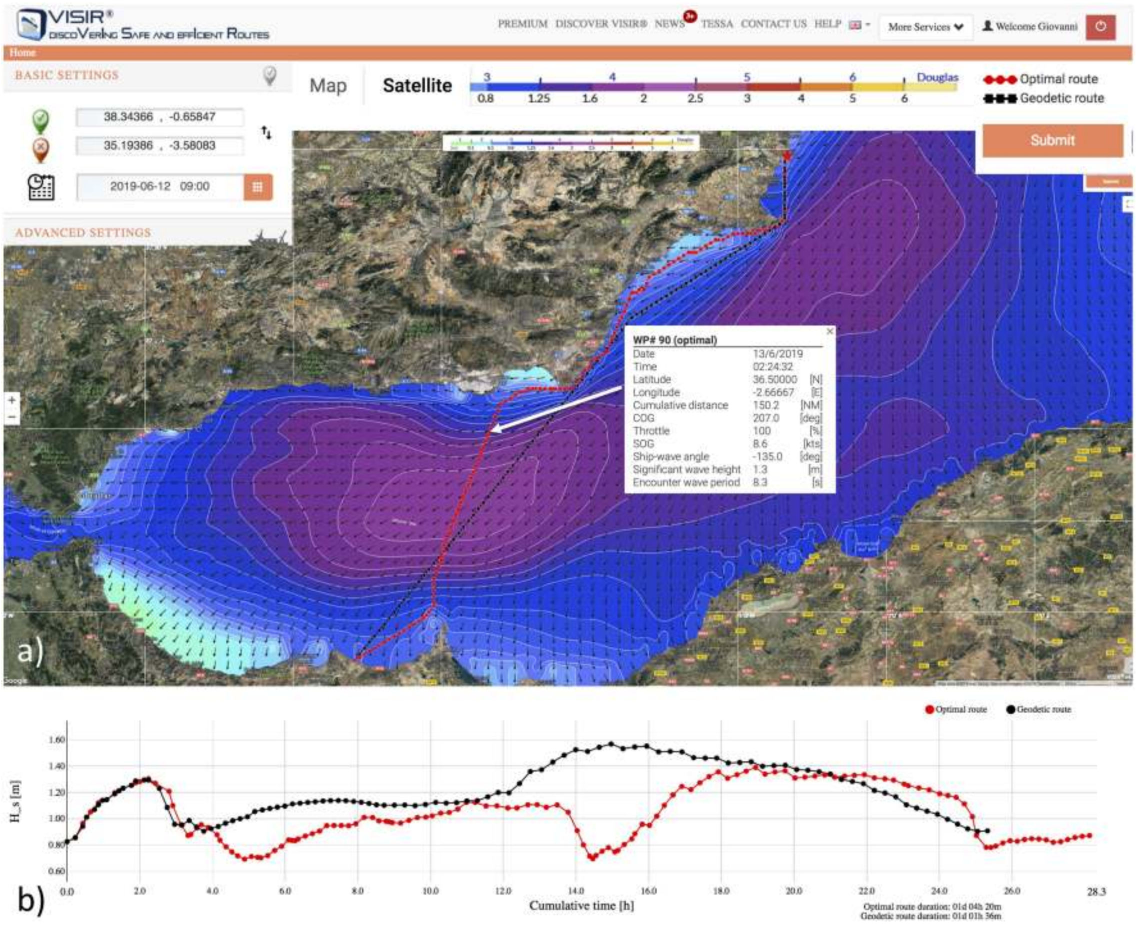
FIGURE 13 | The output and graphics interface for the Oil spill decision support system, called WITOIL. Users can request access by registering http://www.witoil.com/en/join.

capacity of existing systems to include biology, fisheries, etc., and to aid MSFD implementation.

ODYSSEA is aimed at addressing the data gaps that have been identified in the Mediterranean Sea by developing a fully-operational standardized chain of models, comprised of hydrodynamic, wave, water quality, oil spill, fish and mussel population growth components interlinked through a modular interface. Secondary indicators, early forecasts and alarms tailored to user needs will be produced by the platform at Mediterranean and Observatory level, thus supporting the decision-making process of operational users.

GAPS AND PROSPECTS FOR THE NEXT DECADE

Historically, oceanography in the Mediterranean Sea has developed with only limited coordination between the research and environmental institutions involved. The situation today is



38.34366 , -0.65847

35.19386 , -3.58083

2019-06-12 09:00

WP# 90 (optimal)

Date	13/6/2019	
Time	02:24:32	
Latitude	36.50000	[N]
Longitude	-2.66667	[E]
Cumulative distance	150.2	[NM]
COG	207.0	[deg]
Throttle	100	[%]
SOG	8.6	[kts]
Ship-wave angle	-135.0	[deg]
Significant wave height	1.3	[m]
Encounter wave period	8.3	[s]

Optimal route duration: 01d 04h 20m
Geodetic route duration: 01d 01h 36m

FIGURE 14 | Screenshots from VISIR-nav.com web application: **(a)** Main window, with significant wave height (H_s) in shading and contours, wave direction as black arrows, geodetic route as black waypoint markers (wp), optimal route as red wp. The info-window displays information at the selected wp. Departure wp is marked by a red star. Departure and arrival coordinates and departure date and time are given in the box in the top-left. **(b)** H_s profile along both the geodetic and optimal routes. http://www.visir-nav.com/en/join.

changing, and MONGOOS, in coordination with EuroGOOS, are at the core of this transformation, participating in the designing of strategies that translate into more coordinated systems. A good level of data integration amongst institutions willing to share data has been achieved through a strong MONGOOS coordination and collaborative framework. The provision of information to Copernicus and EMODnet is currently effective and already contributes to the future EOOS strategy. Additionally, the Mediterranean community envisages a strategy of connecting oceanography at different spatio-temporal scales to applications that will give reliable, science-based information to policy makers when deciding on prevention/adaptation/mitigation actions against climate change impacts and environmental problems.

However, the challenges of pollution reduction, climate change, and sustainable fisheries show that this is only the starting point for future integrated observing and forecasting systems. These should consider advanced observing, coupled earth system predicting models and tailored end-user products for societal benefit.

Achieving this higher degree of integration is not a simple or sequential process, and multiple lines of action will be followed. The contribution of MONGOOS will be of paramount importance for this transformation. MONGOOS is the natural working framework for the definition of the requirements of such an integrated system. Additionally, MONGOOS will be instrumental in obtaining the resources required for the transformation. Finally, MONGOOS will contribute to the steering of EOOS, via EuroGOOS, to ensure its objectives are properly aligned with the integration process.

A detailed analysis of the gaps, requirements and future strategies in the Mediterranean and Black Sea region was carried out in May 2015 (Tintoré et al., 2015), after the international workshop entitled "The Kostas Nittis Scientific and Strategic Workshop on a coordinated European observing systems strategy," which was organized to honor the work and memory of this forward-looking scientist. An updated analysis of the gaps can be found in the MONGOOS Science and Strategy plan (Sofianos et al., 2018) and the EMODnet Checkpoint report (Pinardi et al., 2017).

Gaps

To define the gaps in the observing and forecasting system, two components of the ocean value chain can be examined: (1) the basic/core services, which consist of observational and forecasting products; and (2) the downstream products that are customized for specific end-users. These two components have different requirements and specific gaps, and thus different solutions and challenges.

In terms of the basic/core products that can be derived from observations, we have reported some of the gaps in coverage in both space and time for the different platforms, which are mainly due to the lack of observing planning at the Mediterranean Sea basin scale. Bonaduce et al. (2016) demonstrated that the absence of sea level stations along the southern coasts means that estimating the basin mean sea level trend is not possible simply from tide gauges.

From a physical EOV point of view, three-dimensional currents are clearly under-sampled throughout the region. The same applies for waves, salinity and water temperature profiling. From a biochemical EOVs point of view, O_2 content measurements are currently lacking, and so it is not possible to determine whether deoxygenation is an active process at the basin scale. The lack of data in both basins does not adequately describe the seasonality of nutrient concentrations and their spatial distribution, particularly in relation to external sources dependent on human activities.

The under-sampling for both physical and biogeochemical EOVs has been partially analyzed by observing system assessment studies (e.g., Observing System Experiments OSEs and Observing System Simulation Experiments OSSEs, see for instance Oke et al., 2015). These conceptual experiments help to evaluate the impact of specific observations on the EOV core product estimates. Previous work has focused on the impact of gliders (Dobricic et al., 2010; Mourre and Alvarez, 2012; Alvarez and Mourre, 2014; Hernandez-Lasheras and Mourre, 2018), Argo T/S profiles, sampling schemes, float positions, Voluntary Observing Ship XBTs (Griffa et al., 2006; Raicich, 2006; Taillandier and Griffa, 2006; Nilsson et al., 2011; Sanchez-Roman et al., 2017), Ferry Box (Korres et al., 2014) and Fishery Observing System (Aydogdu et al., 2016) platforms. These approaches, extended to the whole set of available multiplatform observations and biogeochemical EOVs, should be part of the common strategy to guide future observing system developments and optimize investments.

The monitoring of fresh water runoff (surface and underground) and land-derived pollution is a serious concern for the Mediterranean Sea. The UN Barcelona Convention has over the past 30 years attempted to monitor pollution and develop an ecosystem approach for conservation and management of fisheries, but much more work is required. Other challenges for the monitoring of pollution in the Mediterranean Sea include the rapidly increasing activities of the oil/gas industry over the last 5 years (Alves et al., 2016) and the increase of maritime transport. We do not have yet an adequate system in support of emergency management even if REMPEC has defined several collaboration agreements with the MONGOOS community.

Gaps in the observing system have been also identified for the downstream products that are customized for specific end-users. The EMODnet Checkpoint (Pinardi et al., 2017) has developed an innovative assessment procedure to detect "data adequacy at the basin scale for downstream products." Seven downstream products, referred to as Challenges, were used: wind farm siting, marine protected areas connectivity, oil spill forecasting, climate and coastal erosion, fishery management, eutrophication, and rivers loading and runoff. Data adequacy has been assessed on the basis of two main set of indicators: availability and appropriateness. Availability entails the evaluation of how the input data sets are made available to Challenges (easily found data sets, data set contained in an INSPIRE Catalog, data policy and its visibility, pricing, delivery mechanism, format of the data and responsiveness of the service). Appropriateness entails measuring the quality of the monitoring data for the Challenge products.

From the availability indicators of 266 input data sets (core products), we found that data adequacy is low for 19 categories of monitoring data variables/environmental characteristics at the basin scale (Pinardi et al., 2017). The Checkpoint results show that over 60% of the core products contributing to the monitoring of the Mediterranean Sea are totally or partly inadequate for their non-compliance with INSPIRE Catalog principles. In addition, above 40% of the input data sets contributing to the monitoring of the Mediterranean Sea are partly or totally inadequate for policy visibility, delivery mechanism, data policy and responsiveness.

Challenges and Solutions

The challenges of developing sustained Mediterranean Sea observing and forecasting systems are mainly institutional, at both national and international levels. At the national level, the links between the research and the operational infrastructures must be reinforced in addition to the links among the ocean research community, the meteorological services and the environmental protection agencies. At the international level the collaborative framework must be strengthened, thus raising awareness about the international and European infrastructure built for basic systems and converging efforts toward best practices and open and free data policies.

The level of international coordination required for enhancing the fitness for use of core/basic products and the fitness for purpose of downstream services is demanding, and requires the societal impact of the activities to be maximized at the international level. The UN SDG targets and indicators offer a primary framework of societal challenges (mitigate and adapt to climate change in the coastal and open ocean areas, ocean health, food production, and disaster risk reduction) that can sustain the maintenance and upgrading of the basic/core infrastructure in the search for solutions.

The recent Ocean Visions Joint initiative[25] began addressing the issue of science-based solutions against the adverse impacts of climate change, and the Mediterranean Sea community is

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[25] http://oceanvisions.org/ocean-visions-initiative

beginning to think about this as a potential way forward. At the basis of all these initiatives there has to be the development of knowledge sharing and exchange, free and open data policies and the reinforcement of the science-policy process.

For many of the SDG indicators, the present Mediterranean Sea observational and forecasting system is lacking in space-time resolution for some EOVs. The observational efforts should be strengthened to conveniently monitor the main phenomena occurring in the Mediterranean Sea. In addition, the scientific methodology required to define the right indicators is far from conclusive and further studies are necessary to address this issue. The lack of *in-situ* observations in the Southern Mediterranean and the difficulties accessing these regions is a concern that needs coordinated efforts at an internationally high level. An additional challenge for the Mediterranean Sea is to create synergies between the Marine Strategy Framework Directive, the Barcelona Convention and UN SDGs. Some examples of solutions are those for integrated coastal zone management (Diedrich et al., 2010) and for nature-based solutions in the coastal area (Hendriks et al., 2008), but much more is required.

Some of the challenges are methodological: SDG indicators and solutions should make use of numerical models that integrate the observational data and then interpolate or extrapolate these in time and space. The paradigm of the scientific revolution that has occurred in atmospheric numerical weather predictions has yet to emerge in oceanography (Bauer et al., 2015), and in future the modeling and observational community should work more closely together.

Pinardi et al. (2017) suggest potential solutions to the gaps and challenges listed above. They can be summarized as follows:

1) Strengthen the existing monitoring and forecasting ocean infrastructure (CMEMS, EMODnet, SeaDataNet and the sub-regional systems) by adding to or upgrading it with innovative monitoring technologies and numerical models, including fisheries, habitat, wave data and human activities, and in particular maritime traffic data. Use the MONGOOS framework and coordinate with EOOS through EuroGOOS.
2) Develop a new monitoring strategy for the hydrology and sediment mass balance at the basin scales, while retaining local relevance. Key elements of such new hydrological and sediment mass balance strategies could include the integration of satellites with *in-situ* measurements and the combining of coastal morphodynamics modeling with coastal hydrodynamic predictions.
3) Develop innovative INSPIRE compliant transformation services (cloud-based, etc.) connected to the EMODnet Portals and CMEMS products, based upon an accurate investigation of the stakeholders needs.
4) Strengthen the partnerships between MONGOOS, GOOS, IODE and the atmospheric observing and forecasting community (World Meteorological Organization-WMO) connecting the Mediterranean system to the global met-ocean information infrastructure and its protocols for.

At the basis for future success is maintaining active basic research activities that will address high level scientific goals, which lead to major science breakthroughs, innovations in ocean observations, new operational systems and new paradigms of science-based solutions. Last, ocean literacy and the education of new professionals in the science of ocean operational systems are at the basis of the core infrastructure (Chassignet et al., 2018).

CONCLUSIONS

In this paper we have provided an overview of the status of the Mediterranean Sea observing and forecasting network and the downstream services. The conclusion is that there is a solid base for the core infrastructure and there are advanced examples of downstream services that may have major societal impacts. However, the pathway toward sustainability of this core infrastructure at the level of the Mediterranean Sea basin requires a larger and more intensive collaboration framework to be set up over the next decade, and EOOS could well be a key element in this.

We hope that we have demonstrated that a regional observing and forecasting system can be set up, coordinating national efforts and involving the scientific community in a unique framework. We suggest that the Mediterranean regional observing and forecasting system can be an example of a complex multi-faceted and multi-purpose global ocean observing system as depicted for GOOS (Tanhua et al., 2019). Furthermore, knowing that the Mediterranean is teleconnected with the Atlantic Meridional Overturning Circulation (Volkov et al., 2019) and the Atlantic has obvious impacts in the Mediterranean, it will be particularly important in the future to better interface this regional system to the Atlantic component of GOOS.

The Mediterranean community is ready to contribute to the upgrade of the basic/core infrastructure that will mitigate impacts of climate change, define adaptation strategies and thus reduce the risks of loss of life and property on the coasts and at sea.

AUTHOR CONTRIBUTIONS

JT and NP designed and wrote the paper with significant contributions from the key leading scientists from the Mediterranean Observing and Forecasting Systems and projects (e.g., MOOSE, POSEIDON, ODYSSEA, etc…) and also from MONGOOS, and with specific inputs also from all the other authors.

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