JOURNAL OF OPERATIONAL OCEANOGRAPHY
2021, VOL. 14, NO. S1, s1–s185
https://doi.org/10.1080/1755876X.2021.1946240

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CMEMS OSR5 – Chapter 1

1.1. Introduction

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1.1.1. Copernicus Marine Service status and achievements

The first operational phase 2014–2021 of the Copernicus Marine Service has successfully implemented a unique European Union ocean monitoring and forecasting service (https://marine.copernicus.eu/). Thirty thousand expert downstream services and users are now connected to the service that responds to public and private user needs and policies related to all marine and maritime sectors: maritime safety, coastal environment monitoring, trade and marine navigation, fishery, aquaculture, marine renewable energy, marine conservation and biodiversity, ocean health, climate and climate adaptation, recreation, education, science and innovation. The Copernicus Marine Service organises the value chain that goes from observation to information (Le Traon et al. 2019) and is an essential tool for Ocean Governance (Section 1.4) and sustainable management of the ocean based on comprehensive ocean monitoring and forecasting capabilities.

The Copernicus Marine Service is unique by its coverage and comprehensiveness, its balance between state-of-the-art science and operational commitments, and the consistency of its portfolio where satellite observations, in situ observations, and model simulations are used coherently to describe the physical (blue), biogeochemical (green) ocean and sea-ice (white) state the European regional seas and the global ocean. The Copernicus Marine Service gathers a strong network of European ocean information producers. Thanks to a well-established and organised evolutions of the Copernicus Marine Service system of systems, the capabilities to operate a marine service responsive to user needs and scientific/technological advances have fully been demonstrated (CMEMS General Assembly 2020). The product and service portfolios have evolved from 2015 to 2021 with, in particular, the integration of new parameters (e.g. waves, carbon, turbidity, sea ice thickness and icebergs), the improvement of resolution and quality, longer time series, the full uptake of Sentinel missions (S1, S3 and recently S2) and the development of new means to access and visualise the data.

The Copernicus Marine Service provides invaluable observation and model products to assess and report on past and present marine environmental conditions and to analyse and interpret changes and trends in the marine environment as for example discussed in previous Ocean State Reports, https://marine.copernicus.eu/access-data/ocean-state-report, and as part of the Ocean Monitoring Indicator framework, https://marine.copernicus.eu/access-data/ocean-monitoring-indicators. The CMEMS Ocean State Reports and Ocean Monitoring Indicators provide, in particular, a unique ocean monitoring dashboard for policy and decision makers as well as for the general public to support actions and assess progresses in policy implementation. There have been excellent feedbacks on the annual Ocean State Reports and their high level summaries that are now part of the EU ocean state assessment landscape and provide a high visibility of the Copernicus Marine Service. They have also federated a unique pooling of EU scientific expertise to assess the state of the ocean based on the Copernicus Marine Service ocean monitoring products.

A remaining challege is to establish a comprehensive monitoring of the ocean, a challenge that demands international cooperation. In response, the Copernicus Marine Service has set up important partnerships with GOOS, OceanPredict, GEO and GEO Blue Planet. The UN Decade of Ocean Science for Sustainable Development (https://www.oceandecade.org/) will be a unique opportunity to develop further the required international cooperation to support delivery of the information, action and solutions needed to achieve the 2030 Agenda for Sustainable Development.

1.1.2. Plans for Copernicus 2

The Copernicus Marine Service has developed an ambitious plan for the next phase of the Copernicus programme (Copernicus 2). The objective is to further establish CMEMS products as a worldwide reference, foster further the service uptake and respond to increasing and pressing user and policy needs (in particular the EU Green Deal – see Chapter 1 in the 4th issue of the CMEMS Ocean State Report, Peterlin et al. 2020) for improved ocean monitoring and prediction capabilities.

The plan identifies three levels of implementation for the evolution of the Copernicus Marine Service product and service portfolio over the period 2021–2027: baseline (continuity of service with incremental evolutions), enhanced continuity (major product improvements) and new services.

Baseline will be implemented from the start of Copernicus 2 to ensure the continuity of the present service and maintain a consistent blue, white and green offer. This includes incremental evolutions to improve product quality, integrate future Sentinel missions and new in-situ observations (e.g. Biogeochemical Argo, Claustre et al. 2020), to improve the estimation of product uncertainty and benefit from new capabilities of digital services through the WEkEO DIAS platform (https://wekeo.eu/). User interaction and user engagement will be strengthened by developing dedicated sectorial offers per applications and policies and enhancing the training and capacity building offer. The objective is also to re-enforce the Copernicus programmme consistency by producing marine data for the other Copernicus services and developing sectorial approaches (thematic hubs) with the other Copernicus Services (e.g. Coastal, Arctic).

The enhanced continuity and new services streams will build from present and future H2020 and Horizon Europe R&D projects and will be developed depending on budget and priorities. Improved digital services, ensemble forecasts, higher resolution, step change in Arctic monitoring, air/sea CO_2 fluxes, twentieth century reanalyses are proposed under the enhanced continuity scenario. Coastal, marine biology, climate projection (coastal, ecosystem) are proposed under the new services scenario. A strong priority is, in particular, to offer new services for the coastal ocean through a co-design and co-development approach between the Copernicus Marine Service and coastal marine services operated by EU Member States.

The Copernicus Marine Service Ocean State Reports and Ocean Monitoring Indicators will continue to be an essential component of the Copernicus Marine Service in Copernicus 2. The plan is to foster further the integration with other Copernicus Services and, in particular, with the Climate Change Service (https://climate.copernicus.eu/) to provide an integrated assessment of the state of ocean and climate. Links with international activities and organisations related to ocean and climate assessments (Intergovernmental Panel on Climate Change, Intergovernmental Oceanographic Commission; World Meteorological Organisation; UN World Ocean Assessment, Global Ocean Observing System, Global Climate Observing System, G7 Future of the Seas and Oceans Initiative, UN Decade of Ocean Science) will be strengthened. The Copernicus Marine Service could contribute, in particular, to the development of an international framework for ocean monitoring indicators. The delivery of meaningful Ocean Monitoring Indicators requires an adequate ocean observing system. This dependency will be documented. This is essential to advocate for the sustainability of the ocean observing system.

1.1.3. Major outcomes of the 5th issue of the Ocean State Report

The 5th issue of the CMEMS OSR incorporates a large range of topics for the blue, white and green ocean for all European regional seas, and the global scale over 1993–2019 with a special focus on 2019. As previous reports, this report is organised within four principal chapters:

- Chapter 1 provides the introduction and a synthesised overview, together with an informative section on ocean governance written in collaboration with the European Marine Board (https://www.marineboard.eu/).
- Chapter 2 includes various novel scientific analyses of the ocean state variability at subseasonal, seasonal and multi-annual scales.
- Chapter 3 connects science and policy by reporting science cases of (potential) socio-economic relavance.
- Chapter 4 highlights unusual events during the year 2019.

The reporting and indicators are focused on the seven Copernicus Marine Service regions, i.e. the global ocean, the Arctic, the North-West-Shelf, the Iberia-Biscay-Ireland, the Baltic Sea, the Mediterranean Sea and the Black Sea. The uncertainty assessment based on a ‘multi-product-approach’ is also used here (see von Schuckmann et al., 2018 for more details). The OSR is predominantly based on CMEMS products, and many analyses are complemented by additional datasets. CMEMS includes both satellite and in-situ high level products prepared by the Thematic Assembly Centres (TACs) – including reprocessed products – and modelling and data assimilation products prepared by Monitoring and Forecasting Centres (MFCs). Products are described in Product User Manuals (PUMs) and their quality in the Quality Information Documents (QUID; CMEMS 2016). Within this report, all CMEMS products used are cited by their product name, and download links to corresponding QUID and PUM documents are provided. The use of other products has also been documented to provide further links to their product information, and data source.

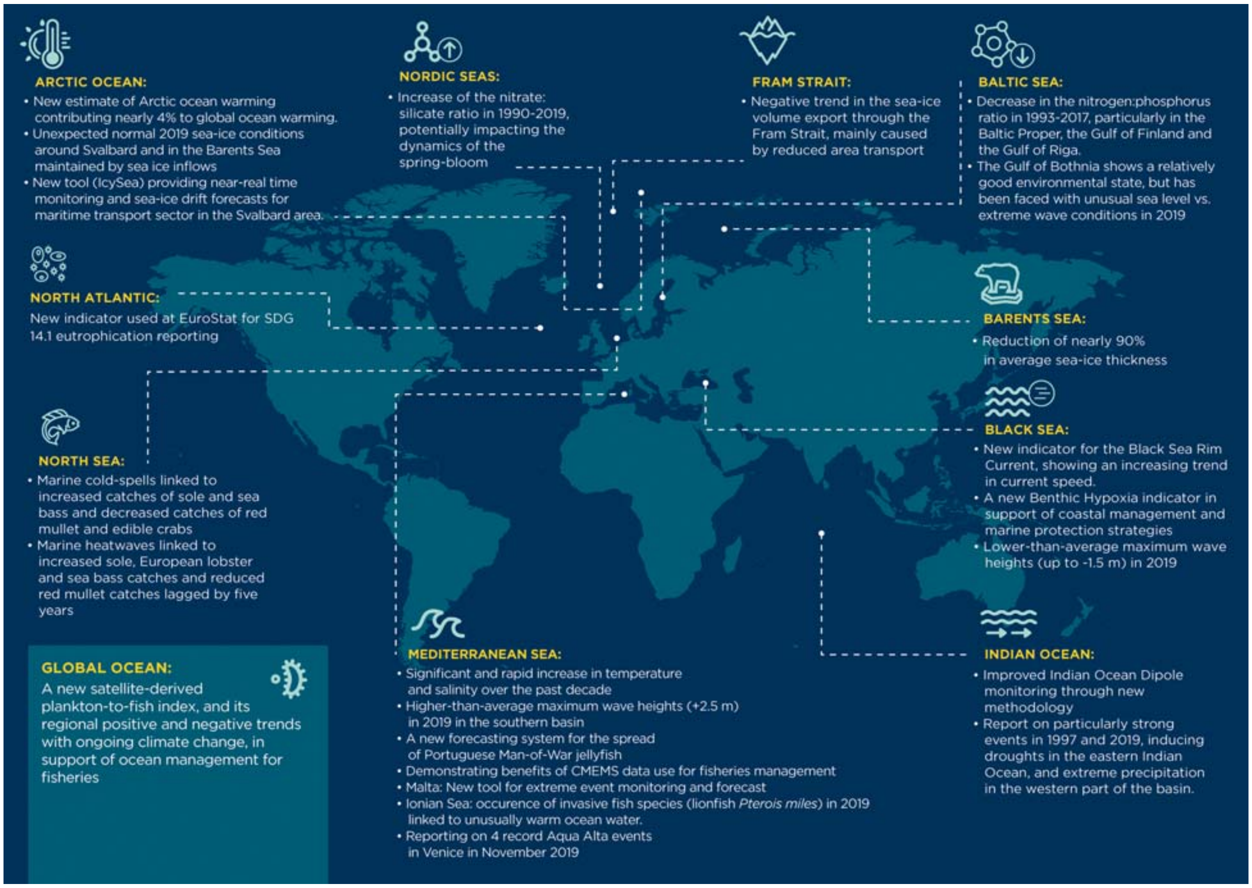
The major outcomes of the fifth issue of the Copernicus Marine Service Ocean State Report are synthesised in Figure 1.1.1, and are summarised below.

Global / Large scale:

Investigations in OSR5 address three topics at large to global ocean scale: the development of an indicator to monitor the eutrophic and oligotrophic state in the ocean; a chlorophyll-a based indicator linked to a plankton-to-fish index as well as an improved indicator for an air–sea coupled mode of variability in the Indian Ocean.

Eutrophication is the process by which an excess of nutrients (mainly phosphorus and nitrogen) leads to increased growth of plant material in an aquatic body – an issue particularly of relevance in coastal regions and areas with restricted water flow. Eutrophication can be linked to anthropogenic activities, such as farming, agriculture, aquaculture, industry and sewage, and results in decreased water quality through enhanced plant growth (e.g. algal blooms) causing death by hypoxia of aquatic organisms. Oligotrophication is the opposite of eutrophication, where reduction in some limiting resource leads to a decrease in photosynthesis by aquatic plants, which might in turn reduce the capacity of the ecosystem to sustain the higher organisms in it. A new indicator of eutrophic and oligotrophic waters proposed in OSR5 derived from satellite chlorophyll-a data (Section 2.4) showed hardly any localities in the North Atlantic where the eutrophic flag was positive in 2019 (i.e. above the 1993–2017 P90 climatological reference). Oligotrophic flags were positive mostly along coastal waters, but also along scattered points within the 30–40°N latitudes. Waters flagged as eutrophic can be then classified as eutrophication or oligotrophication when the eutrophic state is sustained over several years, such as a significant trend over time. This indicator methodology has been distributed to EuroStat in the context of SDG14.1a eutrophication reporting over the period 1998–2019 for all European Seas.

The horizontal gradient of chlorophyll-a derived from remote sensing chl-a data and linked to a



ARCTIC OCEAN:
- New estimate of Arctic ocean warming contributing nearly 4% to global ocean warming.
- Unexpected normal 2019 sea-ice conditions around Svalbard and in the Barents Sea maintained by sea ice inflows
- New tool (IcySea) providing near-real time monitoring and sea-ice drift forecasts for maritime transport sector in the Svalbard area.

NORDIC SEAS:
- Increase of the nitrate: silicate ratio in 1990-2019, potentially impacting the dynamics of the spring-bloom

FRAM STRAIT:
- Negative trend in the sea-ice volume export through the Fram Strait, mainly caused by reduced area transport

BALTIC SEA:
- Decrease in the nitrogen:phosphorus ratio in 1993-2017, particularly in the Baltic Proper, the Gulf of Finland and the Gulf of Riga.
- The Gulf of Bothnia shows a relatively good environmental state, but has been faced with unusual sea level vs. extreme wave conditions in 2019

NORTH ATLANTIC:
New indicator used at EuroStat for SDG 14.1 eutrophication reporting

BARENTS SEA:
- Reduction of nearly 90% in average sea-ice thickness

BLACK SEA:
- New indicator for the Black Sea Rim Current, showing an increasing trend in current speed.
- A new Benthic Hypoxia indicator in support of coastal management and marine protection strategies
- Lower-than-average maximum wave heights (up to -1.5 m) in 2019

NORTH SEA:
- Marine cold-spells linked to increased catches of sole and sea bass and decreased catches of red mullet and edible crabs
- Marine heatwaves linked to increased sole, European lobster and sea bass catches and reduced red mullet catches lagged by five years

GLOBAL OCEAN:
A new satellite-derived plankton-to-fish index, and its regional positive and negative trends with ongoing climate change, in support of ocean management for fisheries

MEDITERRANEAN SEA:
- Significant and rapid increase in temperature and salinity over the past decade
- Higher-than-average maximum wave heights (+2.5 m) in 2019 in the southern basin
- A new forecasting system for the spread of Portuguese Man-of-War jellyfish
- Demonstrating benefits of CMEMS data use for fisheries management
- Malta: New tool for extreme event monitoring and forecast
- Ionian Sea: occurence of invasive fish species (lionfish *Pterois miles*) in 2019 linked to unusually warm ocean water.
- Reporting on 4 record Aqua Alta events in Venice in November 2019

INDIAN OCEAN:
- Improved Indian Ocean Dipole monitoring through new methodology
- Report on particularly strong events in 1997 and 2019, inducing droughts in the eastern Indian Ocean, and extreme precipitation in the western part of the basin.

Figure 1.1.1. Overview on major outcomes of this 5th issue of the CMEMS Ocean State Report.

plankton-to-fish index (Section 3.1) has been shown to be highly valuable to marine biologists and ecosystem modellers and, in turn, to regional fisheries management and authorities facing overexploitation and the effects of climate change. Marine policies will ultimately be efficiently supported by the use of chlorophyll-a gradient as a direct, observation-based, biological variable monitoring the marine ecosystem productivity across a wide range of spatial and temporal scales.

The Indian Ocean Dipole (IOD) is an air–sea coupled mode of variability in the Indian Ocean exacerbating moderate to extreme variations at the air–sea interface such as precipitation and ocean hydrography changes. OSR5 has analysed the classical IOD index – the Dipole Mode Index – based on Sea Surface Temperature (SST), and complemented the analysis with a sea level-based indicator demonstrating the increased performance of IOD monitoring based on a combined use of both indexes (Section 2.9). Results report on two particularly strong events in 1997 and 2019, inducing drought periods in the land areas bordering the eastern Indian Ocean, and extreme precipitation in the western part of the basin.

The North-Atlantic / Arctic gateway

Sea-ice conditions in the North-Atlantic / Artic gateway strongly impact ecosystem, weather, and economic activities, such as tourism, fisheries, and shipping. OSR5 has particularly emphasised blue, white and green oceanographic conditions at Svalbard, the Barent Sea and other areas of the Nordic Seas. The Fram Strait represents the major gateway for sea ice transport between the Arctic and North Atlantic Ocean, affecting the mass balance of the perennial ice cover in the Arctic. Contrary to previous results, OSR5 finds a significant, negative trend in the sea-ice area export through this strait over the last two and a half decades (1993–2019) as affected by a strong reduction of nearly 90% in average sea-ice thickness in the Barents Sea (Section 2.1).

In 2019 however, sea-ice conditions had been surprisingly normal around Svalbard and parts of the Barents Sea, albeit concurrent unusual low sea-ice extent in summer and autumn in the Arctic ocean. The OSR5 results (Section 4.1) have shown that sea-ice (old, and thick) redistribution from the Artic into this area have acted to recover the sea-ice cover and ocean stratification through adding sea ice and freshwater to the region. This supports that large sea-ice inflows act to maintain an Arctic-type ocean climate with a cold, stratified, and sea-ice covered water column and is a key player among others in the Arctic climate system. OSR5 also introduces a new tool (IcySea) providing near-real time monitoring (satellite images from the Sentinel 1 satellites) and sea-ice drift forecasts in the Svalbard area to inform operational planning and safety for the transport and navigation economic sector (Section 3.6).

OSR5 has also addressed Artic ocean warming over the past decades (1993–2019) – a critical missing piece of knowledge for global scale ocean warming linked to the current positive Earth energy imbalance: Currently, global ocean warming estimates are limited between 60° S and 60°N and less is known on the role of ocean warming in areas polewards 60°N latitude. In OSR5, the relative contribution of polar ocean warming north of 60°N to global ocean warming rates accounts for nearly 4% – a comparable value to its area fraction of the global ocean (Section 2.2). The ice-free ocean area warms substantially faster as compared to the ice-covered ocean, and this compensating effect leads to a warming trend of 0.6 (0.7) ± 0.2 $\mathrm{Wm^{-2}}$ for the upper 700 m (full-depth) ocean layer of the pan-Arctic region north of 60°N as consistently derived from the combined analysis of observations and reanalyses data over the period 1993–2019.

The molar nitrate:silicate ratio is an important indicator of nutrient availability related to the requirement of diatoms – a major group of microscopic algae, which underpin ocean biological productivity and transfer carbon from the surface to the deep layers of the ocean when they die. Globally, they are responsible for 40% of marine primary production and 40% of the particulate organic carbon exported to the deep ocean. Consequently, changes in diatom concentration can greatly influence global climate, atmospheric carbon dioxide concentration, and the function of marine ecosystems. OSR5 investigated for the first time a 30-year record (1990–2019) of water column silicate and nitrate in the Nordic Seas (Section 2.3), showing a steady increase of the nitrate:silicate ratio throughout the thirty-year period and linked to concurrent statistically significant decline in surface silicate. For this specific region, less access to silicate and other macronutrients in the Nordic Seas may shorten the spring diatom bloom period and hamper zooplankton growth, which in turn may have consequences for growth and development of commercially important fish stocks in these waters.

Baltic Sea:

A specific evaluation of eutrophication is also proposed for the Baltic Sea based on reanalysis results (Section 2.5) with particular focus on the nitrogen to phosphorus ratio, which has been reported to decrease in the water column across the entire Baltic Sea over the period 1993–2017, particularly in the Baltic Proper, the Gulf of Finland and the Gulf of Riga. An exception is the Gulf of Bothnia, which shows a relatively good environmental state over this period. Decrease in the nitrogen to phosphorus ratio affects phytoplankton blooms, supports nitrogen-fixing cyanobacteria growth, which leads to increased production of organic matter – and its decomposition consequently decreases the oxygen content – and enables eutrophication to endure. In addition to changes in the nutrient ratio, cyanobacteria blooms are also facilitated by ocean warming from climate change. Based on the results obtained in OSR5, it is very likely that the Baltic Sea will continue to experience frequent cyanobacterial blooms in the future.

Even a single passage of an extreme storm associated with high waves forces high sea level at the coast and a rough sea outside the sheltered areas. In the Baltic Sea (Section 4.4), simultaneous high sea level and waves lead to significant coastal erosion and flooding of low-lying areas. Low sea levels may complicate operations of heavily loaded cargo ships at the ports. In Januray 2019 however, a very unusual situation was documented: high waves coincided with a low coastal sea level. In January 2019, the Bothanian Sea had been hit by a severe storm and record-breaking significant wave height of 8.1 m was recorded. Surprisingly, exceptionally low sea levels were concurrently recorded in many coastal stations (as low as −1.1 m), both on the Finnish and the Swedish side of the Gulf of Bothania. As discussed in Section 4.4, the interplay of the extreme event, local sea ice extent and ocean circulation changes have triggered these unusual conditions.

North Sea:
OSR5 also draws a linkage between extreme variability such as marine heat waves and cold spells and key fish and shellfish stocks in the North Sea (Section 3.2). Catches of sole and sea bass increased in years with cold-spells (1994, 1996, 1997, 2010, 2011, 2013 and 2018), while catches of red mullet and edible crabs decreased. For heatwaves (1998, 2002, 2003, 2006, 2007 and 2014–2019), the impact on fisheries catch data lagged the temperature events by five years: sole, European lobster and sea bass catches increased whilst red mullet catches reduced.

Mediterranean Sea:
OSR5 also focuses on the Mediterranean Sea which has been recognised to be a climatic hotspot. During the past decade, its water masses have experienced strong and fast increases in temperature and salinity, responding very rapidly to global warming and to changes in the regional freshwater budget – an outcome that is envisaged to be important for climate science, environmental agencies, concerned citizens as well as regional policy-makers (Section 2.6).

The monitoring of the spatial and temporal evolution of storms is crucial to provide an information service to responsible emergency entities like coastguards and civil protection units which might need to intervene even under harsh weather and sea conditions (Section 4.2). In such circumstances, accurate nowcasts and short-term predictions are essential to prepare interventions that are timely, effective and with minimal risk. This kind of service is also essential to provide information and guidance for safer navigation by avoiding the higher impacted sea areas or delaying transits. OSR5 also discussed a new approach for the Maltese shelf area to predict, monitor, and assess extreme meteo-marine conditions, to verify the evolution of the storms in real time, and to provide improved services to users such as for civil protection, marine safety, and risks to essential assets. The method (Section 4.2) is based on merging complement data from observation and modelling systems (CMEMS products, CALYPSO HF radar network), aided by the support of artificial intelligence techniques in-cooperating knowledge from past extreme events. The methods performance is demonstrated on two extreme events in January and December 2019.

The city of Venice in Italy experienced four exceptionally high tidal peaks in the week from 11 to 18 November 2019, flooding large parts of the city. Venice had not suffered from four successive extreme events within one single week before. The OSR5 results (Section 4.3) show that spring tides coincided with a very high mean November sea level during this week. Additionally, and concurrent with the tidal maximum, strong Sirocco winds pushed Adriatic Sea water towards Venice during three of the four exceptional water level events. For the most extreme event on 12 November, a storm passed over Venice just at the time of the maximum tide. The official forecast underestimated maximum water levels for this event as the model forcing did not resolve the local storm. Higher-resolution atmospheric model fields and the use of satellite wind observations for nowcasting may further improve water level forecasts under extreme conditions.

OSR5 also covers a study on the intensity and geographical distribution of maximum wave height in the Mediterranean and Black Seas over 27 years (1993–2019) using CMEMS wave model hindcasts and the wave model WAVEWATCH III® (Section 2.8). Results show that in 2019 maximum wave heights were smaller than usual in the Black Sea (up to −1.5 m), while in the South Mediterranean Sea higher-than-average wave heights (+2.5 m) are reported linked to atmospheric depressions that rapidly passed over this area.

OSR5 also demonstrated the strong linkage between changes in South Adriatic hydrography as triggered by the ocean circulation – particularly for salinity – and the biodiversity in this area with potential effects on fish species of commercial interest (Section 3.5). These changes in the ecosystem can strongly impact economies and coastal communities that might need to adapt to the declining abundance of traditional target species and/or to the increasing abundance of other species, which previously were secondary to the local market.

The ecological and socio-economic consequences (e.g. on tourism, aquaculture, fisheries) of jellyfish outbreaks on the shorelines are relevant worldwide, and the development of prediction tools is critical to anticipate and mitigate the arrival of the jellyfish blooms (Section 3.4). While the Portuguese Man-of-War is not native to the Mediterranean Sea, their appearance had been reported several times during the past decade in the Gulf of Cadiz and in the Western Mediterranean. OSR5 presents a new forecasting system for the spread of this jellyfish which shows good skills during a strong event in 2018. The main potential benefits of this new forecasting system are to support coastal managers, and to minimise associated socio-economic losses.

Section 3.6 discusses the benefits of integrating the CMEMS variables in combination with trawl surveys into the modelling of fishery independent data for predicting fish species distribution in the Adriatic and Ionian basins. An integrated ecosystem approach is discussed, which incorporates anthropogenic and other environmental stressors into the advice for fisheries management. The results robustly demonstrate that the combined use of data improves the species distribution in the models.

The presence of invasive species in the Mediterranean Sea is much higher than in other European seas, and understanding the reasons behind the range expansion of this invasive species is important for minimising any possible impacts to the already highly pressurised Mediterranean marine ecosystem. OSR5 describes in Section 4.5 sightings of the invasive lionfish *Pterois miles* in the Ionian Sea, together with an analysis of ocean temperature in this region, and in 2019, warm water conditions have favoured the northward spread of this thermophilic species along the coast of the Mani Peninsula and the Greek mainland. These results are critical for ecological modellers and regional stakeholders involved aiming to monitor the spread of this generalist predator in their waters.

Black Sea:
In this 5th issue of the CMEMS OSR, topics tackled for the Black Sea include aspects of the basin-scale circulation, as well as discussing hypoxia monitoring in the northwestern part of the basin. The general circulation in the Black Sea features a cyclonic gyre encompassing the entire basin (Rim Current). OSR5 provides a new method for the Black Sea Rim Current ocean monitoring indicator (Section 2.7). Results over the period 1993–2019 show Rim current speed variations of 30% in close relation to the atmospheric circulation (e.g. wind) and an increase in Rim Current speed of ~0.1 m/s/decade.

During the 1970s to 1990s, large areas of the Black Sea, particularly along the Romanian and Ukrainian coasts, had been hit by severe hypoxia predominantly driven by eutrophication, and this dead zone reached up to 40,000 km^2 at its extreme in the 1990s. OSR5 (Section 3.8) analyses a Benthic Hypoxia index in this area over the period 1992–2019 depicting general recovery from the preceding eutrophication period (1980s), but also a re-increase in the severity of benthic hypoxia for the years 2016–2019 which is attributed to warming atmospheric conditions. Results demonstrate that a joint consideration of oceanographic and climate conditions and riverine and coastal nutrient discharge, incorperated into an operational indicator such as presented in this study could be a critical tool in support of coastal management and marine protection strategies.

1.2. Knowledge and data for international Ocean governance

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1.2.1. What is international Ocean governance?

Covering 71% of the Earth's surface and holding 99% of the area that can be inhabited by life, the Ocean plays a pivotal role in sustaining life on Earth, including through the provision of climate regulation, food, energy, and many other resources. The Ocean, or 'blue', economy in Europe alone was estimated to have a turnover of €750 billion in 2018 (European Commission 2020) and there is significant interest in developing this further through increased jobs and by supporting innovation. However, over-exploitation of the Ocean as a result of human activities is a very real challenge, and coupled with increasing pressures from climate change impacts and pollution, its ability to continue supporting life on Earth is threatened. There is hence a balance to be achieved: in order to continue supporting life on Earth and to achieve the Sustainable Development Goals (SDGs), the Ocean must be productive, clean, healthy, and resilient. For this, we must ensure that human impacts on the Ocean and its