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End-user applications for ocean forecasting: present status description

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Abstract. The direct benefits of developing ocean forecasting systems and of improving the accuracy of the predictions are practically demonstrated through downstream applications. These systems are considered pillars of the blue economy, offering potential for economy, environmental sustainability, the creation of new job opportunities, and actively supporting decision-making. In this paper, the authors outline the main sectors currently benefiting from ocean model products, reviewing the state of the art and potential use for societal activities, management, and planning.

1 Introduction

The blue economy is an increasing sector which includes, amongst other socio-economic sectors, marine living resources, marine non-living resources, marine renewable energy, port activities, shipbuilding and repair, maritime transport, naval activities, search and rescue operations, and coastal tourism. (Fig. 1). The associated economic activities have directly employed close to 4.45 million people and generated around EUR 667.2 billion in turnover and EUR 183.9 billion in gross value added (Rayner et al., 2019b). These sectors offer significant potential for economic growth, sustainability transition, and employment creation, and they ask for innovative, sound, and prompt decision-making support tools. A decision-making workflow needs to understand past and present ocean conditions and forecast future ocean conditions. Accurate predictive capabilities permit the implementation of services for real-time decision-making, multi-hazard warning systems, and anticipatory marine spatial planning. Once the ocean forecast model data are generated, they can be used in a variety of ways. For example, shipping companies can use the data to optimize their routes and avoid areas with dangerous weather or ocean conditions. Fisheries managers can use the data to predict fish populations and optimize their harvests. Environmental agencies can use the data to monitor water quality and detect the spread of pollution, etc. Notably, the Horizon Europe program (2021–2027) has a budget of EUR 95.5 billion (including EUR 5.4 billion from the NextGenerationEU recovery fund), of which at least 35 % will be devoted to support climate-related actions, such as supporting the transition of maritime industries to climate neutrality. Maritime spatial planning (MSP) is a policy framework for mediating between human uses of the ocean and managing their impact on the marine environment. It is considered a key pillar of the sustainable blue economy. Europe's coastal seas, particularly the North Sea and the Baltic Sea, host a highly competitive group of users, such as commercial and private shipping, oil and gas exploitation, pipelines, cables, sand extraction and disposal, wind farms, recreational activities, and fishing, as well as nature reserves and other marine and coastal protected areas (Buck et al., 2004).

The following paragraphs present some examples of how the blue economy is using model data and what its overall impact is.

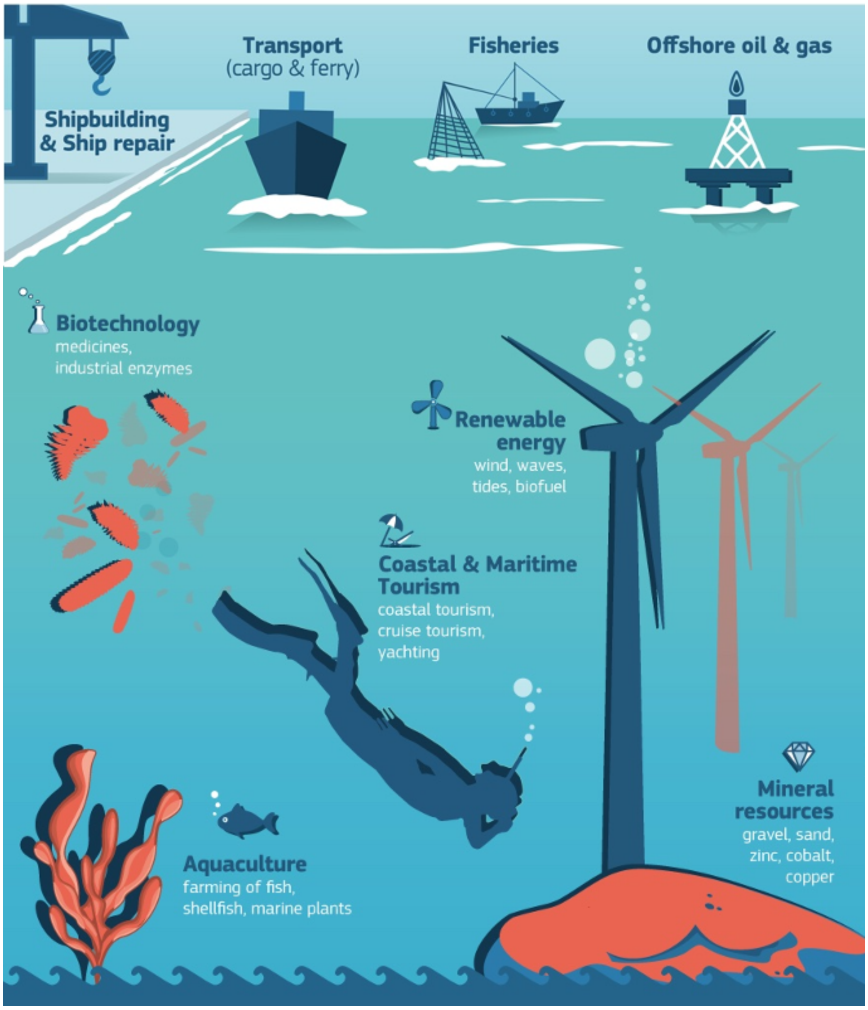

Figure 1. Blue growth, adapted from the EC infographics on blue growth (https://ec.europa.eu/assets/mare/infographics/, © European Union 2014, last access: 31 January 2025).

2 Model data applications in the blue economy

A good collection of examples of the application of ocean forecasting data in the blue economy can be found in the Expert Team on Operational Ocean Forecast Systems (ETOOFS) guide (https://www.mercator-ocean.eu/en/guide-etoofs/, last access: 24 April 2024). The following subsections briefly describe some of these application fields.

2.1 Operational Services for Ports and Cities (OSPAC)

Port and coastal cities need ocean forecasting data for several reasons. A good example of this kind of application can be found on the Operational Services for Ports and Cities (OSPAC) software system, consisting of an integrated set of tools and measuring instruments that provide an operational service to the city and the adjacent port in order to minimize risks and improve environmental management. In these systems, there are two main service layers: the first one includes forecast models of local sea conditions, and, based on these models, a second layer provides real-time alerts on extreme values of coastal variables, such as water quality, currents, and sea state, that are used for a variety of applications (Reboa et al., 2024; Gaughan et al., 2019; NOAA, 2021; OECD, 2016, 2022; Rayner et al., 2019a). The study on the trends and outlook of marine pollution (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea, 2021) reports that most ship-based environmental hazards, such as oil spills or slicks, occur close to city ports. While the situation has significantly improved over the years, the average number of spills per year in 1970 was approximately 79, which has now been reduced by over 90 % to as low as 6 per year (ITOPF, 2020). However, even a single spill can cause severe environmental damage. The extent of damage caused by an oil spill depends on several factors: the quantity of oil spilled, its behavior in the marine environment, the chemicals involved, the sensitivity of the affected marine area, and the wind and weather conditions at the time of the incident. For example, the clean-up and removal efforts following the break-up and sinking of the Bahamas-registered tanker *Prestige*, which spilled 63 200 t of oil on 13 November 2002, lasted more than 2 years. The pollution caused an estimated EUR 884.98 million in damages, with an additional EUR 554.10 million attributed to environmental and moral damages (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea, 2021) – amounting to an environmental cost of roughly EUR 2 million per day. Having OSPAC systems to plan and manage fast and effective responses is key to saving billions of euros in environmental and economic costs.

2.2 Marine transport, surveillance, naval operations, and marine search and rescue (SAR)

Maritime transport plays a key role in the EU economy and trade, estimated to represent between 75 % and 90 % (depending on the sources; EMSA, https://www.emsa.europa.eu/eumaritimeprofile.html, last access: 25 January 2025) of the EU's external trade and one-third of the intra-EU trade. EU passenger ships can carry up to 1.3 million passengers, representing 40 % of the world's passenger transport capacity. Marine surveillance and naval operations are critical to ensuring the security of marine operations. The sector consumes forecasting data on weather and ocean conditions to, for example, determine the optimal route and time of departure for a vessel, optimize the mission route, and minimize risks to personnel and equipment (Novellino et al., 2021; Życzkowski et al., 2019; Bitner-Gregersen et al., 2014; Schnurr and Walker, 2019). These models can help improve the safety and efficiency of marine transport while minimizing fuel consumption and environmental impacts (Wan et al., 2018). Related to naval operations, the search and rescue (SAR) operations use evidence-based methods to plan, execute, and evaluate SAR operations (Futch and Allen, 2019). SAR requires the gathering and processing of relevant data and information, such as weather and ocean forecasts, topography and geography of the area, and the real-time information of the nature of the incident and its evolution (Révelard et al., 2021; Coppini et al., 2016). This information is used, for example, to minimize the search areas.

2.3 Offshore operations

Offshore operations provide access to sources of energy and raw materials necessary for the economy. Ocean forecasting services are crucial for offshore operations: for oil and gas activities, they support oil spill trajectory modeling, data-driven approaches to forecasting production, maintenance support, and many other uses (Keramea et al., 2021); for offshore renewable energy production, they enable the accurate prediction of energy and operational yield efficiency (Uihlein and Magagna, 2016).

2.4 Aquaculture and fish stock management

The EU has highlighted the need for a new strategy for aquaculture to become sustainable and to enable future growth in this sector (COM/2021/236) and the new approach for a sustainable blue economy (COM/2021/240). Currently, the need for blue sector food products in the EU is mostly met through imports, around 60 %, ("The EU Fish Market" 2020 edition, EUMOFA), while EU aquaculture accounts for only 20 % of fish and shellfish supply. The rising population demands radical solutions towards food security, which cannot be solely met through land-based agriculture. Seaweed (macroalgae) aquaculture has the potential to supplement food supplies, enhance the maritime economy, and enable ecosystem services (Maar et al., 2023).

In this framework, forecasting services play an important role by providing valuable information to help improve production efficiency; reduce risks; and ensure sustainable practices, such as production planning. The services help to determine optimal production plans, e.g., size and timing of harvests, based on factors like water temperature, nutrient levels, and fish growth rates. These services also support the impact prediction of environmental factors, such as ocean extremes and pollution levels (Sangiuliano, 2018). Another component of the sustainable blue economy is balancing the need for productive fisheries with the preservation of marine biodiversity, i.e., the fish stock management and maintaining sustainable marine protected areas. By predicting environmental factors like water temperature, salinity, and ocean currents, models also help anticipate shifts in fish behavior and distribution and optimize daily operations. In addition to operational benefits, forecasting models support regulatory compliance by aiding fisheries in adhering to quotas, seasonal closures, and protected area guidelines set by organizations such as the International Council for the Exploration of the Sea (ICES) and regional fishery management bodies.

2.5 Coastal tourism

Coastal tourism plays an important role in many EU member state economies, with a wide-ranging impact on economic growth, employment, and social development. Coastal tourism is the largest blue economy sector, representing 44 % of the gross value added (GVA) and 63 % of the employment of the total EU blue economy. The value of models for coastal tourism extends from short-term weather forecasts to long-term forecasts, including climate change, sea level rise, and tourism demand; forecasting tourism demand using machine learning algorithms; and predicting coastal tourism vulnerability, from dangerous weather and ocean conditions (extreme events), including sea level (storm surge) events and their relevance in inundation and coastal destruction processes (Le Traon et al., 2015), to climate change and sea level rise (da Costa et al., 2024).

2.6 Education

Education and ocean literacy are integral to fostering a sustainable blue economy. By combining formal education with efforts to increase public understanding of the ocean's vital role in supporting life and economies, stakeholders can build a knowledgeable and engaged society. Academic institutions, vocational training centers, and research organizations are developing interdisciplinary programs that integrate technical expertise with environmental stewardship, preparing a workforce adept in ocean sciences, renewable energy, aquaculture, and maritime logistics (Novellino et al., 2022). Ocean literacy initiatives further complement these efforts by raising awareness about marine ecosystems; their resources; and the challenges they face, such as pollution and climate change (see, e.g., https://eurogoos.eu/ocean-literacy-resources/, last access: 25 January 2025). Public campaigns, community engagement projects, and educational outreach help individuals and communities understand the importance of sustainable practices.

3 Perspectives

The future of the blue economy is deeply intertwined with the ability to harness advanced scientific tools, such as ocean forecasting models, to address emerging challenges and seize new opportunities. The European Digital Twin of the Ocean, a cutting-edge initiative combining high-resolution ocean data with advanced simulation capabilities, represents a transformative leap in understanding and managing marine environments. This digital twin enables real-time modeling and prediction of ocean conditions, offering unprecedented opportunities for sectors such as maritime transport, renewable energy, fisheries, and coastal management to make data-driven decisions while aligning the needs and offerings of both the public and private sectors. The integration of on-demand access to computing resources and services further amplifies the potential of the digital twin by enabling scalability, real-time access, and computational efficiency. On-demand high-performance computing platforms make it feasible to process vast amounts of data, perform complex simulations, and deliver actionable insights to stakeholders across industries and regions. These technologies facilitate the democratization of ocean data, ensuring that even small-scale operators can leverage state-of-the-art tools to optimize their activities and align with sustainability goals. A key perspective is the integration of these advancements into a holistic framework that supports sustainable development, equitable resource distribution, and robust regulatory compliance. The transition to ocean-based renewable energy sources, the advancements in sustainable aquaculture, and the growing role of marine spatial planning highlight the need for interdisciplinary approaches that combine ecological stewardship with economic growth. Moreover, scaling solutions through the high-performance computing resources enables seamless collaboration across international borders, fostering knowledge exchange and ensuring that technological progress benefits all nations, particularly those heavily reliant on marine resources. Ultimately, the blue economy offers a pathway to achieving global sustainability goals, providing food security, clean energy, and economic resilience while preserving marine ecosystems.

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