End User Applications for Ocean Forecasting: present status description

Antonio Novellino[1], Alain Arnaud[2], Andreas Schiller[3], Liying Wan[4]

[1]ETT S.p.A., Genoa, Italy
[2]Mercator Ocean International, Toulouse, France
[3]CSIRO Environment, Castray Esplanade, Hobart, Tasmania, Australia
[4]National Marine Environmental Forecasting Center Beijing, China

Correspondence to: Antonio Novellino (antonio.novellino@dedagroup.it)

Abstract. The direct benefit of developing ocean forecasting systems and in improving the accuracy of the predictions is practically demonstrated through downstream applications. These systems are considered pillars of the Blue Economy, offering potential for economy, environmental sustainability, 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, coastal tourism, etc (Figure 1). The associated economic activities directly employed close to 4.45 million people and generated around €667.2 billion in turnover and €183.9 billion in gross value added (Rayner et al., 2019). These sectors offer significant potential for economic growth, sustainability transition, employment creation, as well as 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 is generated, it 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 programme (2021-2027) has a budget of €95.5 billion (including €5.4 billion from the Next Generation of the EU 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 or 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 are presenting some examples of how the blue economy is using model data and which is its overall impact.

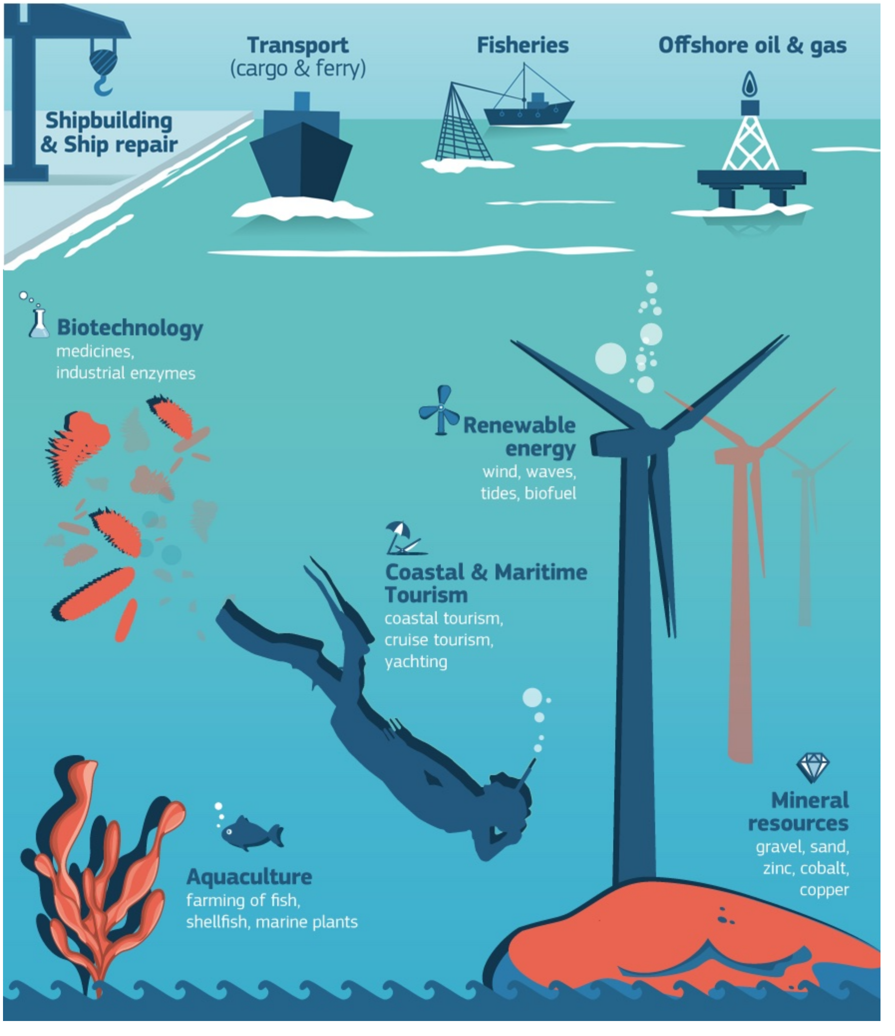

Figure 1: Blue Growth (adapted from the EC infographics on Blue Growth)

2 Model data applications in Blue Economy

A good collection of examples of application of Ocean Forecasting data in Blue Economy can be found in the Expert Team on Operational Ocean Forecasting Systems (ETOOFS) Guide[1]. The following section describes briefly some of these application fields.

Operational Services for Ports and Cities

Port and coastal cities need ocean forecasting data for several reasons. A good example of this kind of applications can be found on the OSPAC (Operational Services for Ports and Cities) 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 A et al, 2024; Gaughan et al., 2019; NOAA, 2021; OECD, 2016; OECD, 2018; Rayner et al., 2019). The study on trends and the outlook of marine pollution (REMPEC 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 six 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 tonnes of oil on November 13, 2002, lasted more than two years. The pollution caused an estimated €884.98 million in damages, with an additional €554.10 million attributed to environmental and moral damages (REMPEC 2021) - amounting to an environmental cost of roughly €2 million per day. Having OSPAC systems to plan and manage fast and effective responses is key to save billions of euros in environmental and economic costs.

Marine Transport, Surveillance, Naval Operations and marine 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[2]) 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 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,

[1] https://www.mercator-ocean.eu/en/guide-etoofs/

[2] https://www.emsa.europa.eu/eumaritimeprofile.html

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 needs gathering and processing 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.

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 yields operational efficiency (Uihlein and Magagna, 2016).

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" EUMOFA 2020 edition), 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 are helping 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 are also supporting 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 area. By predicting environmental factors like water temperature, salinity, and ocean currents, models also help anticipate shifts in fish behavior and distribution and optimizing 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.

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 tourisms goes from short term weather forecast to long-term including climate change, sea level rise, and tourism demand, forecasting tourism demand using machine learning algorithms, and predicting coastal tourism vulnerability, e.g. 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).

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/). Public campaigns, community engagement projects, and educational outreach help individuals and communities understand the importance of sustainable practices.

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 EU 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 performing 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, 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 performing 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.

References

Bitner-Gregersen, E.M., Bhattacharya, S.K., Chatjigeorgiou, I.K., Eames, I., Ellermann, K., Ewans, K., Hermanski, G., Johnson, M.C., Ma, N., Maisondieu, C., Nilva, A., Rychlik, I., Waseda, T.: Recent developments of ocean environmental description with focus on uncertainties. Ocean Engineering 86, 26-46. https://doi.org/10.1016/j.oceaneng.2014.03.002, 2014.

Buck, B.H., Krause, G., Rosenthal, H.: Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints. Ocean & Coastal Management, 47(3–4), 95-122. https://doi.org/10.1016/j.ocecoaman.2004.04.002, 2004.

Coppini, G., Jansen, E., Turrisi, G., Creti, S., Shchekinova, E. Y., Pinardi, N., Lecci, R., Carluccio, I., Kumkar, Y. V., D'Anca, A., Mannarini, G., Martinelli, S., Marra, P., Capodiferro, T., and Gismondi, T.: A new search-and-rescue service in the Mediterranean Sea: a demonstration of the operational capability and an evaluation of its performance using real case scenarios, Nat. Hazards Earth Syst. Sci., 16, 2713–2727, https://doi.org/10.5194/nhess-16-2713-2016, 2016

da Costa V.S., Alessandri J., Verri G., Mentachi L., Guerra R. and Pinardi N.: Marine climate indicators in the Adriatic Sea. Front. Clim. 6:1449633. https://www.frontiersin.org/journals/climate/articles/10.3389/fclim.2024.1449633/full

ITOPF (2020). Oil tanker statistics 2019[3].

Futch, V., and Allen, A.: Search and Rescue Applications: On the Need to Improve Ocean Observing Data Systems in Offshore or Remote Locations. Frontiers in Marine Science, 6, https://doi.org/10.3389/fmars.2019.00301, 2019.

Gaughan, P., Hallinan, D. and Reilly, K.: Using Economic Cost Benefit Analysis Methodologies to underpin the sustainability and strategic planning of Coastal Ocean Research Infrastructures in Europe. OCEANS 2019 - Marseille, 1-8. https://doi.org/10.1109/OCEANSE.2019.8867276, 2019.

Keramea, P., Spanoudaki, K., Zodiatis, G., Gikas, G., Sylaios, G.: Oil Spill Modeling: A Critical Review on Current Trends, Perspectives, and Challenges. Journal of Marine Science and Engineering. 9(2):181. https://doi.org/10.3390/jmse9020181, 2021.

Le Traon, P. Y., Antoine, D., Bentamy, A., Bonekamp, H., Breivik, L. A., Chapron, B., … Wilkin, J.: Use of satellite observations for operational oceanography: recent achievements and future prospects. Journal of Operational Oceanography, 8(sup1), s12–s27. https://doi.org/10.1080/1755876X.2015.1022050, 2015.

Maar, M., Holbach, A., Boderskov, T., Thomsen M., Buck B.H., Kotta J., Bruhn A.: Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. Commun Earth Environ 4, 447. https://doi.org/10.1038/s43247-023-01116-6. 2023

[3] https://www.itopf.org/fileadmin/uploads/itopf/data/Documents/Company_Lit/Oil_Spill_Stats_publication_2020.pdf

National Oceanic and Atmospheric Administration (NOAA): The Ocean Enterprise 2015–2020: A study of U.S. New Blue Economy business activity: https://ioos.noaa.gov/project/ocean-enterprise-study/, 2021.

Novellino, A., Alba, M., Bonofiglio, L., Brotto, P., Mazzarello, M., Besio, G., Mazzino A, Corgnati L, Mantovani C, Berta M, Ottaviani, E.: SINDBAD: An Innovative Med Sea Situation Awareness Tool. Bollettino di Geofisica Teorica ed Applicata, 62. https://bgo.ogs.it/sites/default/files/pdf/IMDIS2021.pdf. 2021.

Novellino, A., Bonofiglio, L., Cimmino, V., Napoletani, L.: STEP - SmarT Education Platform. In N. Callaos, J. Horne, B. Sánchez, M. Savoie, Y. Wang (Eds.), Proceedings of the 13th International Multi-Conference on Complexity, Informatics and Cybernetics: IMCIC 2022, Vol. I, pp. 147-152. International Institute of Informatics and Cybernetics. https://doi.org/10.54808/IMCIC2022.01.147. 2022

OECD: The Ocean Economy in 2030, OECD Publishing, Paris. https://doi.org/10.1787/9789264251724, 2016.

OECD: Valuing Sustained Ocean Observations: An OECD background paper. OECD Publishing, Paris, 2018.

Rayner, R., Jolly, C., Gouldman, C.: Ocean Observing and the Blue Economy. Front. Mar. Sci. 6. https://doi.org/10.3389/fmars.2019.00330, 2019.

Rayner, R., Gouldman, C., & Willis, Z.: The Ocean Enterprise – understanding and quantifying business activity in support of observing, measuring and forecasting the ocean, Journal of Operational Oceanography, 12:sup2, S97-S110, DOI: 10.1080/1755876X.2018.1543982, 2019.

REMPEC 2021: Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (2021). Study on trends and outlook of marine pollution from ships and activities and of maritime traffic and offshore activities in the Mediterranean, Floriana. ISBN: 978-9918-0-0322-8, 2021.

Révelard A., Reyes E., Mourre B., Hernández-Carrasco I., Rubio A., Lorente P., Fernández C.D.L., Mader J., Álvarez-Fanjul E. and Tintoré J.: Sensitivity of Skill Score Metric to Validate Lagrangian Simulations in Coastal Areas: Recommendations for Search and Rescue Applications. Front. Mar. Sci. 8:630388. https://doi.org/10.3389/fmars.2021.630388 2021.

Sangiuliano, S.J.: Analysing the potentials and effects of multi-use between tidal energy development and environmental protection and monitoring: A case study of the inner sound of the Pentland Firth. Marine Policy, 96, 120-132. https://doi.org/10.1016/j.marpol.2018.08.017, 2018

Reboa A, Besio G, Cutroneo L, Geneselli I, Gorbi S, Nardi A, Piccione ME, Regoli F, Capello M.: The EU Interreg Project "GEREMIA" on waste management for the improvement of port waters: results on monitoring the health status of fish as bioindicator. Environ Sci Pollut Res Int. 2024 Mar;31(12):17617-17633. https://doi.org/10.1007/s11356-023-25587-4. 2023.

Schnurr, R. E.J., and Walker, T.R.: Marine Transportation and Energy Use. Reference Module in Earth Systems and Environmental Sciences, ISBN 9780124095489. https://doi.org/10.1016/B978-0-12-409548-9.09270-8, 2019.

Uihlein, A., and Magagna, D.: Wave and tidal current energy – A review of the current state of research beyond technology. Renewable and Sustainable Energy Reviews, 58, 1070-1081. https://doi.org/10.1016/j.rser.2015.12.284, 2016.

Wan, Z., Ge, J., Chen, J.: Energy-Saving Potential and an Economic Feasibility Analysis for an Arctic Route Between Shanghai and Rotterdam: Case Study From China's Largest Container Sea Freight Operator. Sustainability, 10(4), 921. https://doi.org/10.3390/su10040921, 2018.

Życzkowski, M., Szłapczyńska, J., and Szłapczyński, R.: Review of Weather Forecast Services for Ship Routing Purposes. Polish Maritime Research, 26(4), 80-89. https://doi.org/10.2478/pomr-2019-0069, 2019.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Data and/or code availability

This review considered the results and data listed in the references.

Authors contribution

Authors equally contributed to the design and writing

Acknowledgements

This activity was indirectly supported by authors activities under the Copernicus Marine Service and EMODnet programs and the following projects: H2020 NAUTILOS (ct. 101000825), HE OLAMUR (ct. 1011094065), HE EFFECTIVE (ct. 101112752), HE BLUECLOUD2026 (ct. 101094227).