“OceanPredict’24 symposium: advancing ocean prediction science for societal benefit”

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ABSTRACT

The world’s oceans are undergoing major and rapid changes in response to human pressure. The OceanPredict'24 Symposium was a historic gathering of the ocean prediction scientific community to discuss recent progress and how best to address societal challenges. Advancing ocean monitoring and prediction services is essential to sustainably manage the Ocean, protect marine biodiversity, and support climate change mitigation and adaptation policies. Additionally, the capacity to produce and distribute ocean information can help increase the effectiveness of government functions, such as search and rescue, marine regulations, maritime industries in ship routing, and tourism, to name only a few. In this context, the community has expressed the need for sustainable ocean environment prediction capabilities and has identified the main challenges to advance the science of ocean prediction for the benefit of society. First, ocean observations (in situ and satellite) form the basis of research and forecasting capabilities and there is a need to significantly increase investment in continuous and improved observing capacities and data sharing. Second, machine learning and digital twins using cloud computing are emerging as major tools to improve systems and services and can help foster collaborations along the ocean prediction value chain. Third, advances in modelling and data assimilation are essential to improving our understanding of ocean processes, especially regarding the complex interactions between the earth system components (ocean, atmosphere, sea ice, land and ecosystems). Finally, this symposium highlighted the critical need for international coordination on ocean prediction capacities, which has been initiated as part of the United Nations’ (UN) Decade of Ocean Science for Sustainable Development (2021-2030). As an outcome of this symposium, a call for the global mobilization of ocean science stakeholders to advance ocean prediction will be launched at the UN Ocean Conference in Nice in June 2025.

INFO BOX

What: OceanPredict’24 invited ocean modelling and prediction scientists from physics, sea-ice and biogeochemistry, observation specialists, industry representatives, service providers and users of ocean data and products from across the international operational oceanography community to engage in science sessions and discussions to explore and define the future direction of ocean prediction.

When: 18-22 November 2024

Where: UNESCO, Paris, France, and online streaming
https://www.oceanpredict24.org/

1. Introduction: a symposium to identify the challenges faced by the ocean prediction science community

The Ocean is undergoing dramatic changes due to climate change, pollution, and the (over)exploitation of marine resources. These changes impact the blue (physics), green (biogeochemistry, ecosystems) and white ocean (sea ice). Advanced ocean monitoring and prediction capabilities are urgently required to sustainably manage the Ocean, protect marine biodiversity, and support climate change mitigation and adaptation policies. OceanPredict is an international research and development program focused on advancing the science of ocean prediction by supporting the development of global and regional ocean analysis and forecasting systems. Through exchanging knowledge, OceanPredict fosters the development of new capabilities and enhances collaboration within the wider operational oceanography community by organizing regular events (thematic meetings, workshops, symposiums, summer schools). OceanPredict initiated the ForeSea programme, endorsed by the UN Decade of Ocean Science for Sustainable Development (2021-2030, hereafter referred to as UN Decade), to improve the science, capacity, efficacy, use, and impact of ocean prediction systems and to contribute to a seamless ocean information value chain, from observations to end users, for economic and societal benefit, thereby making ocean prediction science more impactful and relevant. OceanPredict/Foresea has close interactions with the CoastPredict UN Decade programme and engages actively in the framework of the OceanPrediction UN Decade Collaborative Center (OP-DCC).

The OceanPredict (formerly GODAE and GODAE OceanView) symposiums have been held periodically since the inception of the Global Ocean Data Assimilation Experiment (GODAE) in 1998. The OceanPredict'24 Symposium “Advancing Ocean prediction science for societal benefit”, organized by OceanPredict/ForeSea in collaboration with UNESCO's Intergovernmental Oceanographic Commission (UNESCO-IOC) was held at the UNESCO headquarters in Paris. The event included plenary sessions, splinter groups, posters, and townhall/roundtable discussions. It marks a significant milestone in global ocean prediction science as it brought together 350 on-site participants (20 poster sessions and 21 oral sessions) and attracted 1,500 online registrations from around the world, highlighting the importance of ocean prediction within the UN Decade. The online participation represents a considerable increase in visibility, as the previous symposium in Halifax in 2019 brought together about 300 participants in total.

The OceanPredict'24 symposium, organized around seven main themes, "Ocean prediction: past, present, and future", "Coastal / Regional prediction", "Polar Ocean / Sea Ice prediction", "Global / Basin-scale / Open Ocean prediction", "New developments in ocean prediction", "Ocean prediction (systems and) services", and "User applications and societal benefits", underscored both the significant recent progress to develop regional and global operational ocean prediction capacities and the need for internationally coordinated efforts to advance operational oceanography and ocean prediction in response to increasing societal needs. This structure allowed the community to review and summarize the current state of our ocean prediction capabilities and to identify key challenges for the coming years. Section 2 summarizes which challenges were identified for the community, section 3 focuses on challenges for coastal prediction, and section 4 on challenges for Polar Ocean prediction. In section 5 global and regional ocean prediction challenges are listed, and section 6 highlights the emerging machine learning (ML) based developments. Directions to improve ocean prediction systems and services are identified in section 7, and finally the connection with users and societal benefit is discussed in section 8.

2. Ocean prediction, past, present and future

The first sea surface temperature (SST) satellite observations which provided global coverage of observations became available in the 1980s (Minnett et al., 2019). With the first altimetric satellites in the 1990s (Le Traon et al., 2025), it became possible to monitor and predict the mesoscale and short-term global ocean environment changes (up to approximately 10 days ahead). High-performance computing and data assimilation advances enabled the development of the first global eddy-permitting ocean forecasting models in the 2000s (Schiller et al., 2018). The ability of these forecasting systems to describe and forecast the subsurface ocean and their overall quality strongly improved thanks to the global coverage of in situ subsurface measurements provided by Argo floats since 2005 (Riser et al., 2016, Zilberman et al., 2023)

Over the last decade or so we've seen an explosion in the number and diversity of ocean prediction centres and services, which support a large and growing number of users. This new operational oceanographic capability faces a variety of opportunities and important challenges, including how to exploit artificial intelligence (AI), creating and operating ocean digital twins, supporting emerging capabilities in a rapidly changing ocean environment and adopting processes for global scale interoperability. Moreover, to meet the many challenges involved in maintaining ocean observation, monitoring, and prediction capacities for the benefit of society, it is necessary to develop an international structure to coordinate efforts to align science, services, governance, and innovation.

In this regard, the OP-DCC provides a framework for further developing OceanPredict/ForeSea activities. This approach implies the creation of a community to foster ocean prediction activities, and the co-development of key technical assets, such as the OP-DCC atlas of ocean prediction systems, a guide for the architecture for ocean forecasting systems and guidelines to define an "Operational Readiness Level" (ORL, Alvarez Fanjul et al., 2024).

Many international entities and coordination bodies (Global Ocean Observing System GOOS, World Meteorological Organisation WMO, Group for Earth Observations (GEO) Blue Planet, …) were present at the symposium to exchange ideas and develop a common vision. Ensuring ongoing and future support and resources for ocean prediction capabilities are crucial, as well as sustained in situ and satellite observation networks to support the full value chain. Important questions raised included enhancing public-private partnerships and the role of the private sector in developing and sustaining ocean prediction capabilities, observation networks, and encouraging innovation, while reconciling the private sector's need for monetization in conjunction with providing public societal benefits.

3. Fostering exchanges between coastal ocean forecasters

Coastal oceans, as heavily used and impacted regions facing diverse human and environmental pressures, require state-of-the-art science-based decision support and tools. Characterized by complex geometries, the non-linear and complex interactions of various processes, including circulation, tides, waves, freshwater fluxes, ocean/atmosphere coupling, biogeochemical cycles, ice dynamics, sediment transport, and the land/sea interactions, coastal oceans have added complexity requiring correspondingly more complex, detailed, and finer-resolution modelling. The paucity of observations in many coastal regions, combined with short time-space scales, also represents a significant challenge for coastal forecasting systems (Benveniste et al., 2019). Coastal forecasting systems use a variety of models with different vertical coordinates, structured or unstructured grids, and numerical conservation schemes. High-resolution and accurate modelling and data assimilation (DA) are essential and must address intricate model and data errors (Kourafalou et al., 2015; Staneva et al.

2024). AI approaches were highlighted for their potential in these domains (see Section 6). Novel approaches also include coupling ocean and hydrological models; using unstructured meshes to represent flows on scales ranging from 1-10 meters to 100 kilometers, e.g. in estuaries; and coupled physical-biogeochemical (BGC) data assimilation using hyperspectral ocean colour data. The usefulness of nonhydrostatic models to the end user requires further evaluation.

Several points for future discussion among coastal forecasters emerged, including the mismatch in resolution between atmospheric forcing (low) and ocean applications (high), and the need for realistic ensemble spreads. The availability of physical and biogeochemical river inputs and lateral boundary conditions is also a common concern, and a challenge for the development of future digital twins of the ocean.

The importance of observations was emphasized, for instance in improving forecasting skill using DA of HF radar surface velocity data. The expansion of coastal observation networks, evaluated thanks to Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) (Edwards et al., 2024), is expected to reduce model errors for water mass transport and mesoscale structure representation, as well to improve the representation of biogeochemical processes.

4. Polar ocean prediction: a focus on rapid changes in the Arctic

Operational modelling and prediction for the rapidly changing Arctic need to address the blue, white (Bertino and Holland 2017) and green ocean (Myksvoll et al., 2023). Significant new challenges and opportunities are arising due to increasing ice-free periods and the poleward migration of species due to global warming. Satellite observations are invaluable for monitoring and predicting polar seas, with promising new missions, such as CRISTAL, CIMR and ROSE-L, in the next decade. Lack of in situ data remains a strong concern. In particular, polar regions remain a critical gap in the global coverage of Argo. Reduced Arctic ice cover and new technologies have permitted some advances in this area, but sustained funding for Arctic Argo is much needed.

Ocean modelling in the Arctic is faced with a variety of specific challenges due to its inherent complexity, the sparsity of observations and the high model resolution needed to represent meso and submesoscale dynamics (Dupont et al., 2015). Additional complexities arise from ice-wave and ice-ocean-atmosphere interactions. The polar oceans are sensitive to heat, moisture, and momentum fluxes between the ocean, ice, and atmosphere to changes in the marginal ice zone and heterogeneous ice cover. Salinity is extremely variable in the Arctic and plays a crucial role in determining the freezing point, stratification, and overturning circulation. Additionally, sea ice thickness influences freshwater inputs, salinity-driven overturning/stratification, heat budget, and momentum transfer.

The assimilation of new satellite-derived sea-ice-thickness and high-latitude salinity observations in ocean and sea ice models, and the use of AI to accelerate forecasting capacities (see section 6) are strong opportunities and challenges for improving polar ocean prediction. Recent advances in sea ice models include modified ice rheologies, thermodynamics, and the inclusion of ice/wave interactions. The organisation of regular intercomparisons of ocean and sea ice prediction systems, in collaboration with the sea-ice community (International Ice Charting Working Group IICWG), would provide a measure of progress in the coming years. The start of 2025 to 2034 UN Decade of Action for Cryospheric Sciences and the future International Polar Year in 2032-2033 are unique opportunities to develop international cooperation.

5. Key trends and challenges for global and regional ocean prediction

Global and basin-scale systems are evolving towards ensemble forecasts, providing several realisations for the same forecast period, thus allowing probabilistic representation of the ocean prediction. Ensemble forecasting offers significant benefits over deterministic approaches by addressing reliability with uncertainty estimates (Leutbecher and Palmer 2008) and increasing predictive skill and the forecast horizon (e.g. up to one month) (Thoppil et al. 2021, Peterson et al., 2022). Advances from ensemble predictions notably support risk assessment and planning; however, challenges include the high computational cost and potentially estimating uncertainties from various earth system components.

Indeed, many global systems tend to allow additional interactive feedback across earth systems components. Notably, ocean/atmosphere coupled models are necessary for forecasting and studying hurricanes and cyclones (Liu et al. 2011, Mogensen et al. 2017, Scoccimarro et al. 2017, Gentile et al. 2021). Additionally, there exists a growing need for improved coupling with biogeochemistry and ecosystem models (Fennel et al. 2022) to better support the operational oceanography community in evaluating integrated challenges and addressing the effectiveness and safety of proposed approaches, such as industry-driven geoengineering solutions for marine carbon dioxide removal solutions (Oschlies et al., 2025). Marine heatwaves are an increasing issue (Capotondi et al., 2024), highlighting the need for community exchanges on their definition and predictability, as well as on their compound impacts on the marine environment.

Ocean observing systems, both in situ and remote sensing, are essential for effective ocean monitoring and forecasting at global, regional, and coastal scales (Liu et al., 2015). The design of emerging observing systems and refined observing strategies require coordinated OSEs and OSSEs, complementing each other for robust results. The Flagship OSE/OSSE project SynObs, a project of UN Decade under ForeSea, helps meet this need (Fujii et al., 2024). Studies under SynObs highlight the impact of satellite altimetry, SST, and Argo using novel validation techniques. Some contributions showed that a dedicated satellite mission for total surface current velocities (TSCV) and advanced coastal monitoring is needed. It was noted that that extending Argo physical and biogeochemical observations to the full water column of the open ocean, and to polar areas and marinal seas, as implemented by One Argo (Roemmich et al. 2019) requires further funding and design refinement, with the ocean modelling community being called to demonstrate Argo's value and allocate resources effectively. Moving towards constraining mesoscale to sub-mesoscale, successful assimilation of SWOT (Surface Waters and Ocean Topography) data was presented, with further work needed on sensitivities to different data assimilation configurations. Regarding biogeochemistry and ecosystems prediction, many new developments rely on a sustained BGC-Argo observation network, for example local parameter optimisation using these profiles, with potential application to larger domains. The use of modelling platforms, such as the Framework for Aquatic Biogeochemical Models (FABM), to increase the interoperability of BGC and ecosystem models was discussed, aiming to eventually facilitate collaboration and progress.

6. New developments in Ocean Prediction : close-up on Machine Learning

Numerous presentations throughout the symposium demonstrated the growing maturity of a range of machine learning (ML) applications in the field of ocean prediction. The number of ML-based contributions in the session dedicated to new developments in ocean prediction (Fig 1) was comparable to that of DA contributions. ML is used to identify relationships between predictors (e.g., parameters, location, time) to produce or expand observational data, such as high-resolution currents (Garcia et al., 2025), the BGC-Argo nitrate and carbon dataset (Bittig et al., 2019, Mignot et al., 2023), and sub-surface salinity from surface data (Buongiorno Nardelli 2020). ML is now used to develop new AI-based ocean and sea ice forecasts (Wang et al. 2024, El Aouni et al. 2024, Cui et al. 2025). ML is also employed to predict additional diagnostic variables beyond the state variables of existing models, such as harmful algae blooms (Silva et al. 2024). These recent ML advances bring new ocean data users into the ocean forecasting community, as well as contribute to improving existing ocean forecasting systems. ML model bias correction and parametrisation, such as ML stochastic modelling, are being explored and developed, along with emulators for optimizing models and data assimilation. Novel hybrid data assimilation approaches are mixing variational, ensemble and ML methods, exploring the use of ML for multiscale error modelling and the expansion of ensembles.

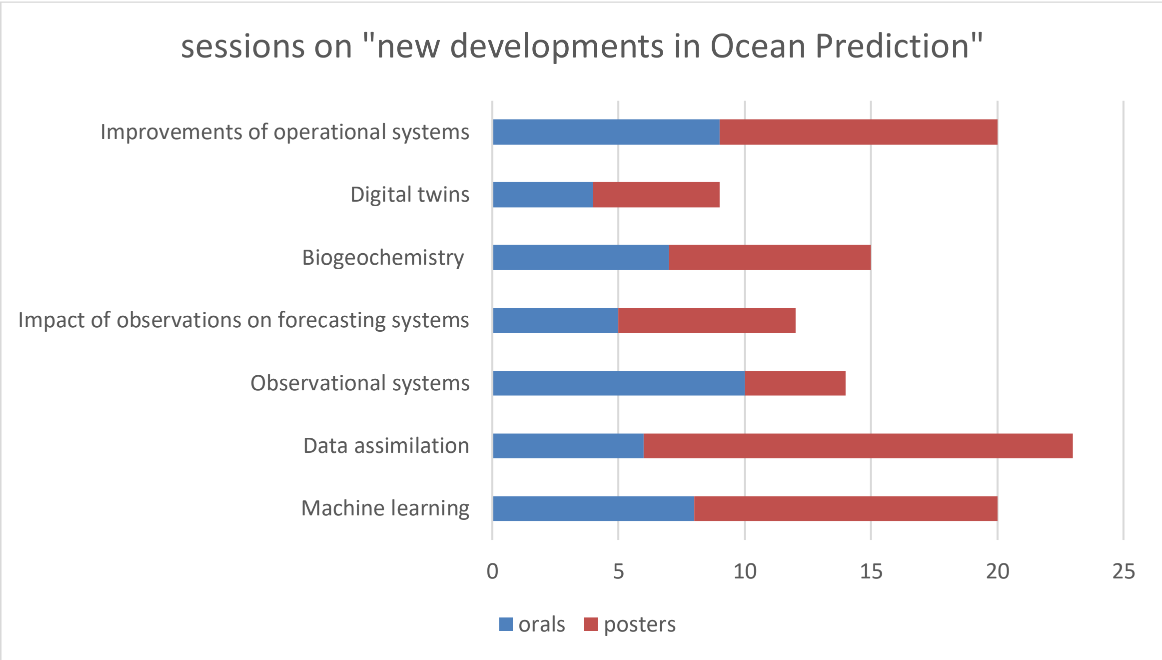

Figure 1: Total number of contributions accepted in each session for the theme "new developments in Ocean Prediction". For each session the proportion of oral presentations is given by a blue bar, and that of poster presentations by an orange bar.

Machine-learning developments are particularly relevant in the context of the recent growth of Digital Twins of the Ocean (DTO), which are dissemination and/or computing platforms leveraging the latest advances in cloud computing and data sharing. The DTOs aim at facilitating access to ocean prediction forecasting systems and data for a wide range of applications and users, and at facilitating the co-design of forecasting systems. For example, the European Digital Twin of the Ocean (EDITO) platform is testing the integration of traditional and ML ocean forecasting capacities, including model codes, together with focused applications (e.g., marine biodiversity and species habitats, ship routing) and what-if scenarios (e.g., nature-based solutions for climate change adaptation). The Digital Twins for

Ocean Robots (Forget, 2024) framework leverages Estimating the Circulation and Climate of the Ocean (ECCO) reanalyses to access, analyse, and simulate the global fleet of ocean observing devices (i.e., ocean robots) that monitor climate change.

7. Ocean Prediction systems and services

Reports from ocean prediction systems and services emphasized the importance of links with users, established by providing reliable, tangible, and trustworthy information. These links can be established through effective dissemination of fit-for-purpose information and associated advice, including information on reliability and conditions of use. Regular training sessions with users also provide an opportunity to better understand their needs. On the development side, locally optimized systems that are co-designed with stakeholders help to ensure engagement and support. On the dissemination side, service agencies need solid infrastructure, including information management systems, open data repositories, and user-friendly access platforms. Effective hazard communication should use a variety of digital methods that support both basic and more sophisticated technologies (e.g. from SMSs and USSD codes for cell phones to mobile applications for smartphones and internet connected devices) as well as more traditional methods (e.g. a coloured flag system on beaches for rip-warmings). Developing interoperable Digital Twins, together with effective collaboration frameworks during the UN Decade, provides an opportunity to better address challenging needs and increase the impact of ocean prediction services for users. An important underlying challenge will be to provide adequate reliability and usability information for a wide range of new services.

Using an agreed set of metrics called “Class 4” (Hernandez et al., 2018), OceanPredict participants have been evaluating and intercomparing the performance of their global systems in observation space. This multi-system intercomparison needs to be extended and sustained as a routine activity for ocean forecasting systems. This evaluation and intercomparison framework, together with improved data sharing capacities, enables to fully assess the potential of multi-system forecasts. Operational systems are continuously improved and benefit from close interaction with users who provide the detailed feedback fundamentally needed to identify and correct system weaknesses.

In the field of the reanalysed past ocean, new historic reanalyses at global and basin scale (eg., the Arctic) emerge, which are important for assessing long-term changes. For instance, accurate long time series, with well-documented strengths and weaknesses, are also key to training AI models (see Section 6). The "Marine Environment Reanalyses – Evaluation Project" (MER-EP) initiative, launched by Mercator Ocean International (Yang et al, 2025), will join forces with the Copernicus Marine Service, OceanPredict, GOOS, and CLIVAR communities to provide up-to-date user-oriented evaluations of existing blue, white and green global and basin-scale ocean reanalyses in the framework of the UN Ocean Decade. Reinforcing links with the WMO (e.g., to facilitate access to atmospheric forcing) and considering longer reanalyses perspectives also appear to be essential for comprehensive service delivery.

8. User applications and societal benefit

Existing marine observational and modelling products are significantly employed in monitoring the health and resilience of the ocean. Specific tools (AI, nesting, relocatable ocean modelling platforms, etc.) are needed in addition to available marine products to address the requirements of specific applications, such as sustainable fisheries, oil spills, search and rescue, and aquaculture farms. The aim is providing reliable and accurate information to society, decision makers, local authorities, and economies. Examples of such existing interfaces were presented during the symposium, including the daily automated nowcast/forecasts of the red tide trajectories (Liu et al., 2023) and the pollutant plume evolution (Liu et al., 2024) in the USA, and the operational forecasting of marine heat waves to inform the fishing community in China (Li et al., 2023). Being end-user oriented, the Copernicus Marine Service (Le Traon et al., 2019), with its 90,000 registered users, serves as a framework for enabling and enhancing the implementation of ocean health and resilience and blue economy applications, with the additional benefit of providing information about the quality of products. The Integrated Marine Debris Observation System (IMDOS, Maximenko et al., 2029) also was introduced, highlighting coordination and guidance for establishing a sustainable global observing system and facilitating open access to data.

There are various mechanisms and organisations for bridging the gap between science and society, as illustrated in Figure 2. GEO Blue Planet, the Group on Earth Observations (GEO) ocean and coastal arm, develops links between data and decision makers to provide useable information that aids informed decision making and policies in the pursuit of sustainable development.

Figure 2: Several coordination bodies act to connect ocean prediction science to society and to action at the government level

9. Conclusion

With the ocean covering 71% of the earth, maritime activities are essential to the global economy and security, as well as to the daily life of at least 37% of the world's population who live in coastal communities. The ocean is undergoing dramatic changes resulting from multiple stressors, such as pollution and overfishing, superimposed on climate-change-induced warming and acidification, endangering the capacity of the ocean to continue serving as a major life resource and as a regulator of the earth climate. Those risks for the health of the planet necessitate advanced monitoring and prediction capabilities dedicated to the ocean environment. These needed capabilities and capacities include observations, analysis systems, prediction models, computing resources, and coordination entities. Stakeholders, including governments, the private sector, and citizens, must engage and mobilize to achieve sustainable management of the ocean's shared resources. Access to sustained, fit-for-purpose in situ observations, spanning physics to chemistry to biology, is crucial, as is the application of higher-resolution and innovative space-based observations. Coastal areas need specific attention to address local processes and their connection to the regional and global ocean. Polar regions, especially the Arctic, require extended observation and prediction capacities due to significant societal impacts. Improved probabilistic forecast capacities at basin and global scales are essential for risk assessment, particularly for ocean biogeochemistry and ecosystem models. Machine learning advancements and cloud-based digital twins offer major opportunities that must be seized for delivering more actionable science-based services. In the meantime, further progress in modelling and data assimilation is essential to improving our understanding of ocean processes and the complex interactions between ocean physics, ocean ecosystems, the atmosphere, sea ice, and land. Following this symposium, all programs supporting ocean prediction science and applications will convene at the One Ocean Science Congress in Nice (June 3-6, 2025) and the UN Ocean Conference (June 8-13, 2025) to foster collaboration and drive progress in ocean prediction science, thereby enabling and supporting sustainable development.

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