# A description of existing Operational Ocean Forecasting Services around the Globe

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**Abstract.** Predicting the ocean state in support of human activities, environmental monitoring, and policy-making across different regions worldwide is fundamental. To properly address physical, dynamical, ice, and biogeochemical processes, numerical strategies must be employed. The authors provide an outlook on the status of operational ocean forecasting systems in 8 key regions including the Global Ocean: the West Pacific and Marginal Seas of South and East Asia, the Indian Ocean, the African Seas, the Mediterranean and Black Sea, the North-East Atlantic, the South and Central America Seas, the North America (including the Canadian coastal region, the United States, and Mexico) and the Arctic.

The authors initiate their discussion by addressing the specific regional challenges that must be addressed, and proceed to discuss the numerical strategy and the available operational systems, ranging from regional to coastal scales. This compendium

serves as a foundational reference for understanding the global offering, demonstrating how the diverse physical environment—ranging from waves to ice—and the biogeochemical features besides ocean dynamics can be systematically addressed through regular, coordinated prediction efforts.

## 1 Introduction

The vast and dynamic nature of the world's oceans plays a critical role in shaping global climate, supporting biodiversity, and sustaining human economies. Accurate ocean forecasting is essential for a variety of applications, including maritime navigation, fisheries management, disaster preparedness, and climate research. As such, the ability to predict ocean conditions with precision is of paramount importance to scientists, policymakers, and coastal communities alike.

Over the past few decades, significant advancements have been made in the field of ocean forecasting, driven by improvements in observational technologies, numerical modelling, and computational capabilities. Satellite remote sensing, autonomous underwater vehicles, and enhanced buoy networks have expanded our ability to monitor oceanic parameters with unprecedented resolution and coverage. Concurrently, sophisticated numerical models, integrating physical, chemical, and biological processes, have improved the accuracy and reliability of ocean predictions.

Despite these advancements, the status of ocean forecasting varies widely across different regions of the world. Factors such as technological infrastructure, scientific expertise, and financial resources influence the development and implementation of forecasting systems. Some regions have established comprehensive and highly accurate forecasting capabilities, while others struggle with limited data availability and outdated methodologies.

This paper aims to provide a comprehensive overview of the current state of ocean forecasting services across various regions globally (reanalysis services are not contemplated). By examining the technological, scientific, and operational aspects of forecasting systems in different parts of the world, we seek to identify both the strengths and gaps in existing capabilities.

The main inventory for operational ocean forecasting services existing today is the Atlas of these services hosted on the OceanPrediction Decade Collaborative Centre (DCC) web site[1]. In this already growing inventory more than 150 worldwide systems are described in detail showing a comprehensive picture of the activity in this field (Figure 1).

The following sections describe, starting with global systems and analysing region by region, the situation across different regions of the world Ocean.

## 2 Global Ocean Forecasting Services

Historically, Global Ocean forecasting efforts were initially focused on naval operations and scientific research, with early models developed to support strategic planning and military navigation. The advent of global observing systems, such as satellite altimetry and Argo floats, provided unprecedented datasets, leading to significant improvements in model accuracy.

[1]https://www.unoceanprediction.org/en/atlas

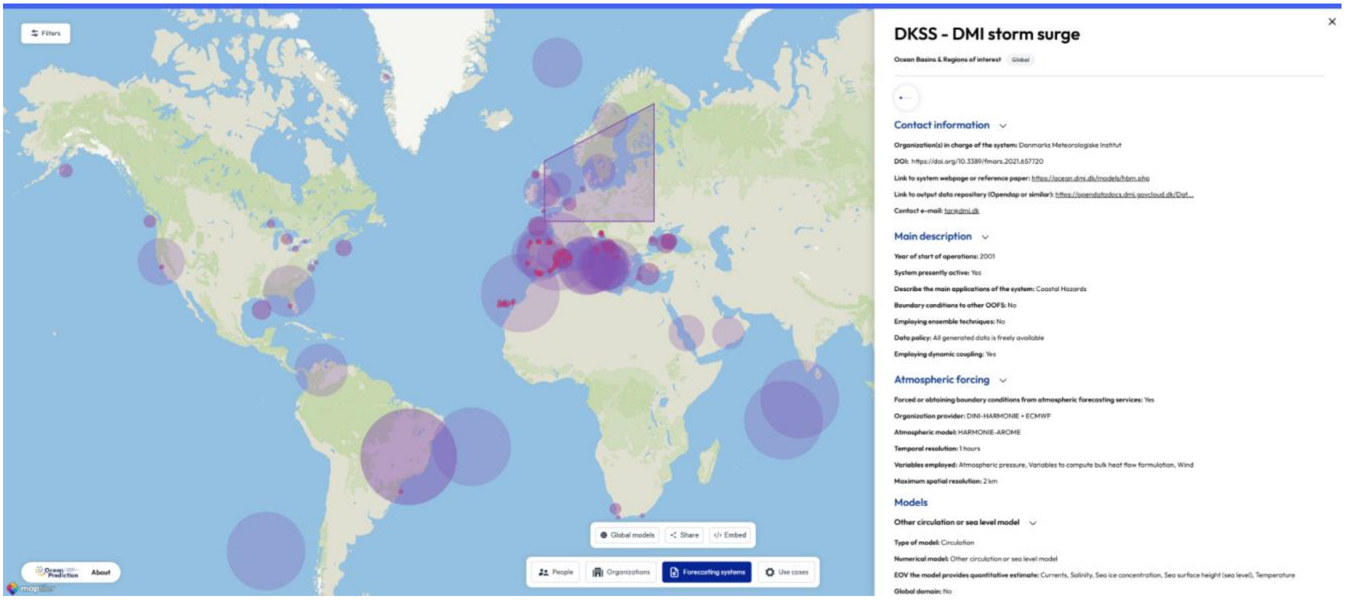


**Figure 1. The OceanPrediction DCC Atlas (https://www.unoceanprediction.org/en/atlas/models).**

With the establishment of initiatives such as the Global Ocean Data Assimilation Experiment (GODAE) in the late 1990s and early 2000s, operational oceanography moved toward a coordinated, global-scale framework. These efforts laid the foundation for modern global ocean forecasting services, which now provide continuous, high-resolution forecasts tailored for various sectors, including fisheries, shipping, offshore energy, and climate services.

Today, global operational ocean forecasting systems are operated by multiple institutions worldwide, using state-of-the-art ocean circulation and sea ice models coupled with data assimilation techniques. These models are forced by atmospheric reanalysis and forecast systems, integrating satellite and in-situ observations to improve the accuracy of predictions. The outputs of these systems are crucial for understanding ocean dynamics, predicting extreme events such as hurricanes and marine heatwaves, and supporting policy decisions related to climate change adaptation and marine resource management.

Table 1 shows the global systems already registered in the OceanPrediction DCC Atlas and their main characteristics. All the detailed information about these systems can be found at the OceanPrediction DCC Atlas. To the knowledge of the authors, only a few systems remain to be incorporated into this inventory: LICOM operated by the Institute of Atmospheric Physics (China), and NAVY-ESPC and GOFS3, both developed by the Naval Research Laboratory (USA).

Other interesting characteristics can be derived from the replies not shown in the area. For the circulation models, the number of vertical layers range from 29 to 98, being Z-coordinates the most used system (4 systems). All the systems (except some wave systems) use data assimilation, but only 2 are making use of ensemble techniques.

**Table 1. Global Ocean Forecasting services on the OceanPrediction DCC Atlas.**

| System | Organization | Forecasted EOV | Numerical model(s) | Horizontal grid type | Maximum resolution |
|---|---|---|---|---|---|
| Global Ocean Analysis and Forecast System (Copernicus Marine GLO-MFC) | Mercator Ocean International | Currents, Salinity, Sea ice concentration, Temperature, Sea State (waves), biogeochemistry variables | NEMO, MFWAM, and PISCES | Regular | 9 km |
| FIO Ocean Forecasting System | First Institute of Oceanography | Currents, Ocean surface heat flux, Salinity, Sea ice concentration, Sea State (waves), Temperature | MOM - GFDL and MASNUM wave model | Curvilinear (MOM) and Regular (MASNUM) | 10 km |
| neXtSIM-F | Nansen Environmental and Remote Sensing Center | Sea ice concentration | neXtSIM - Next Generation Sea Ice Model | Regular | 4 minutes |
| Global FOAM | Met Office | Currents, Salinity, Sea ice concentration, Sea surface height (sea level), Temperature | NEMO and Wavewatch III | Curvilinear | 7 km |
| INCOIS GLOBAL HYCOM | Indian National Centre for Ocean Information Services | Currents, Salinity, Sea surface height (sea level), Temperature | HYCOM - HYbrid Coordinate Ocean Model | Regular | 25 km |
| MOVE-JPN | Meteorological Research Institute | Currents, Ocean surface heat flux, Ocean surface stress, Salinity, Sea ice concentration, Sea surface height (sea level), Temperature | MRI.COM V4 | TriPolar Coordinate System | 15 minutes |
| Real Time Ocean Forecasting System (RTOFS) | National Oceanic and Atmospheric Administration | Currents, Salinity, Temperature | HYCOM | TriPolar Coordinate System | 9 km |

| | | | | | |
|---|---|---|---|---|---|
| Hurricane Forecast Analysis System (HAFS) | National Oceanic and Atmospheric Administration | Currents, Salinity, Sea State (waves), Temperature | HYCOM | Curvilinear | 1 km |
| INPE wave prediction system | National Institute for Space Research | Sea State (waves) | Wavewatch III | Regular | 15 minutes |
| INCOIS-WAVEWATCH III | Indian national centre for ocean information services | Sea State (waves) | Wavewatch III | Regular | 10 km |
| Global Ocean Forecast System GOFS16 | Centro Euro-Mediterraneo sui Cambiamenti Climatici | Currents, Ocean surface heat flux, Salinity, Sea ice concentration, Sea surface height (sea level), Temperature | NEMO - | TriPolar Coordinate System | 3 km |
| Global Ice Ocean Prediction System | Environment and Climate Change Canada | Currents, Salinity, Sea surface height (sea level), Temperature, sea ice properties (concentration, thickness, snow depth, temperature, internal pressure) | NEMO and CICE | TriPolar Coordinate System | 12 km |
| Chinese Global operational Oceanography Forecasting System | National Marine Environmental Forecasting Center | Currents, Salinity, Sea ice concentration, Sea surface height (sea level), Temperature | MaCOM | Unstructured | 5 minutes |
| JCOPE-FGO | Japan Agency for Marine-Earth Science and Technology | Currents, Salinity, Sea State (waves), Sea surface height (sea level), Temperature | POM | Regular | 10 km |

The data sources employed for assimilation change from one system to another, being the used ones ARGO profiles, satellite altimetry, satellite Sea Surface Temperature (SST), buoy data, drifters, XBT, and gliders. Six systems are using dynamic coupling between different models or model components. All systems, but one, are providing the data to third parties, directly or after a specific request. Surprisingly, almost half of the systems declare not being validated operationally. The forecast horizon is usually between 5 to 10 days.

It is interesting to note that in regions where regional and coastal systems are scarce, global services have become a main source of information for many applications. In African seas, for example, outputs from the global services are disseminated on a local web portal. Bandwidth is cited as the most common problem affecting the accessibility of global forecast services. Some countries provide bulletins in pdf format, some add local value to global services by developing and disseminating optimized. Examples of the variety of use types are provided here:

- Mauritius (using Copernicus Marine GLO-MFC products): the Mauritius Oceanography Institute provides a web portal[2] (affiliated with GMES and Africa) that outputs a regional subset of global sea-state forecasts. Monthly bulletins are targeted at users from the marine and fisheries realm for monitoring purposes and are a source of information for researchers and the scientific community.
- Kenya (using INCOIS services): the Kenyan Meteorological Department provides daily and weekly marine forecast bulletins (https://meteo.go.ke/).
- Mozambique (using INCOIS services): Integrated Ocean and Information System for Mozambique, developed by the INCOIS project Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES).
- South Africa (using NCEP-GFS[3]-Wave and Copernicus Marine GLO-MFC products): the South African Weather Service uses the NCEP-GFS, as well as currents from the Copernicus Marine Service forecasts to run an operational regional and coastal wave and storm surge model (Barnes & Rautenbach, 2020). Additionally, they disseminate regional information based on Copernicus Marine forecasts.
- South Africa (using Copernicus Marine GLO-MFC products) added regional value to Copernicus Marine products: e.g., marine heat waves, location of the Agulhas Current (e.g. distance from shore), and SST anomalies in an operational service. The tools are currently being integrated into the web portal.

## 3 West Pacific and Marginal Seas of South and East Asia

In the Western Pacific and Marginal Seas of South and East Asia (WPMSEA), Ocean Forecasting systems are particularly important due to the region's vulnerability to tropical cyclones, tsunamis, and other oceanic phenomena, as well as socio-economic development needs.

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[2] https://moi.govmu.org/gmes/forecast

[3] https://www.nco.ncep.noaa.gov/pmb/products/gfs/

### 3.1 Regional and Coastal Forecasts

In this region, it is very frequent that the regional systems also include nested coastal applications, so the description is merged in a single section.

The Japan Coastal Ocean Predictability Experiments (JCOPE[4]) system, developed by the Japan Agency for Marine-Earth Sciences and Technology (JAMSTEC) based on the Princeton Ocean Model, is a dynamic ocean monitoring and forecasting system (Miyazawa et al., 2009, 2021). Originally tailored for the western North Pacific at eddy-resolving resolutions, JCOPE is now extended to cover the global ocean with a new eddy-resolving quasi-global ocean reanalysis product, the JCOPE Forecasting Global Ocean (JCOPE-FGO). The model covers the global ocean from 75°S to 75°N except for the Arctic Ocean, with a horizontal resolution of 0.1° × 0.1° and 44 sigma levels. The validation against observational data demonstrates JCOPE-FGO's effectiveness, while assessments using satellite data show its capability in representing upper ocean circulation (Kido et al., 2022). The significance of river forcing for accurately representing seasonal variability is emphasized by highlighting the inclusion of updated global river runoff in JCOPE-FGO and its significant impacts on near-surface salinity.

Kyusyu University in Japan operates several real-time ocean forecasting systems based on the Research Institute for Applied Mechanics Ocean Model (DREAMS[5]) system. This 3-dimensional ocean model is formulated in spherical coordinates with a horizontal resolution of approximately 1.5 km and features 114 vertical levels (Liu and Hirose, 2022). Its domain covers a rectangular region southwest of Japan, including part of the East China Sea shelf and the deep Okinawa Trough.

The Mass Conservation Ocean Model (MaCOM) model (Feng et al., 2024) is a newly established and operated global circulation model developed at National Marine Environmental Forecasting Centre (NMEFC) in China (Figure 2). This model adopts a complete physical framework, the key feature of which is mass conservation, enthalpy conservation, salt conservation, and based on pressure coordinates. The MaCOM system is used from global (~ 10km) to coastal (~100m) forecasts and replaces several previously used models in NMEFC. The LASG / IAP Climate System Ocean Model (LICOM) Forecast System (LFS) is another forecast system from China that maintains a horizontal resolution of 3600×2302 grids (1/10°) and 55 vertical levels. Assessments indicate that LFS performs well in short-term marine environment forecasting. For example, LFS is also able to forecast the marine heatwaves around the China Sea, especially in the South China Sea and East China Sea (Li et al., 2023). The surface wave-tide-circulation coupled ocean model developed by the First Institute of Oceanography (FIO-COM) is another global model with an emphasis on tidal mixing (Qiao et al., 2019). The model is developed in close partnership with the Intergovernmental Oceanographic Commission of UNESCO Sub-Commission for the Western Pacific (WESTPAC). MaCOM ocean forecast systems also provides regional as well as coastal forecasts on scales from kilometres to meters with various applications from oil spill forecasts and fishery to ice drifts and marine heat waves.

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[4]https://www.jamstec.go.jp/jcope/htdocs/e/jcope_consortium.html
[5]https://dreams-c1.riam.kyushu-u.ac.jp/vwp/html/vwp_about.html.ja

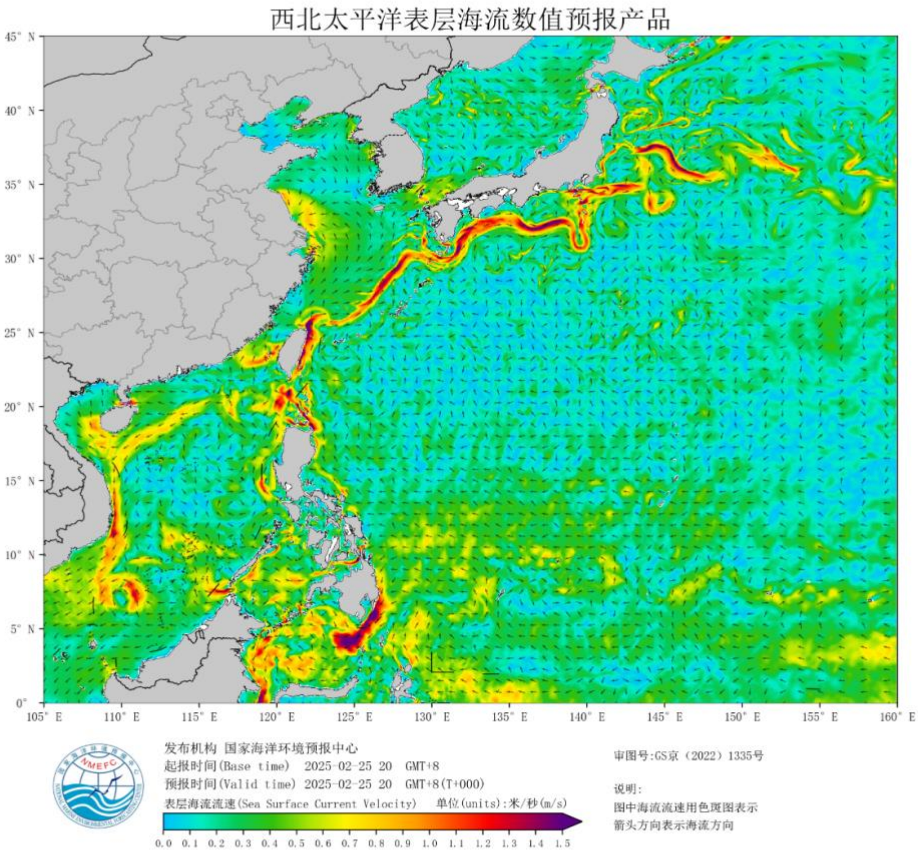


**Figure 2. Surface currents derived from MACOM system (source: https://english.nmefc.cn/ybfw/seacurrent/WestNorthPacific).**

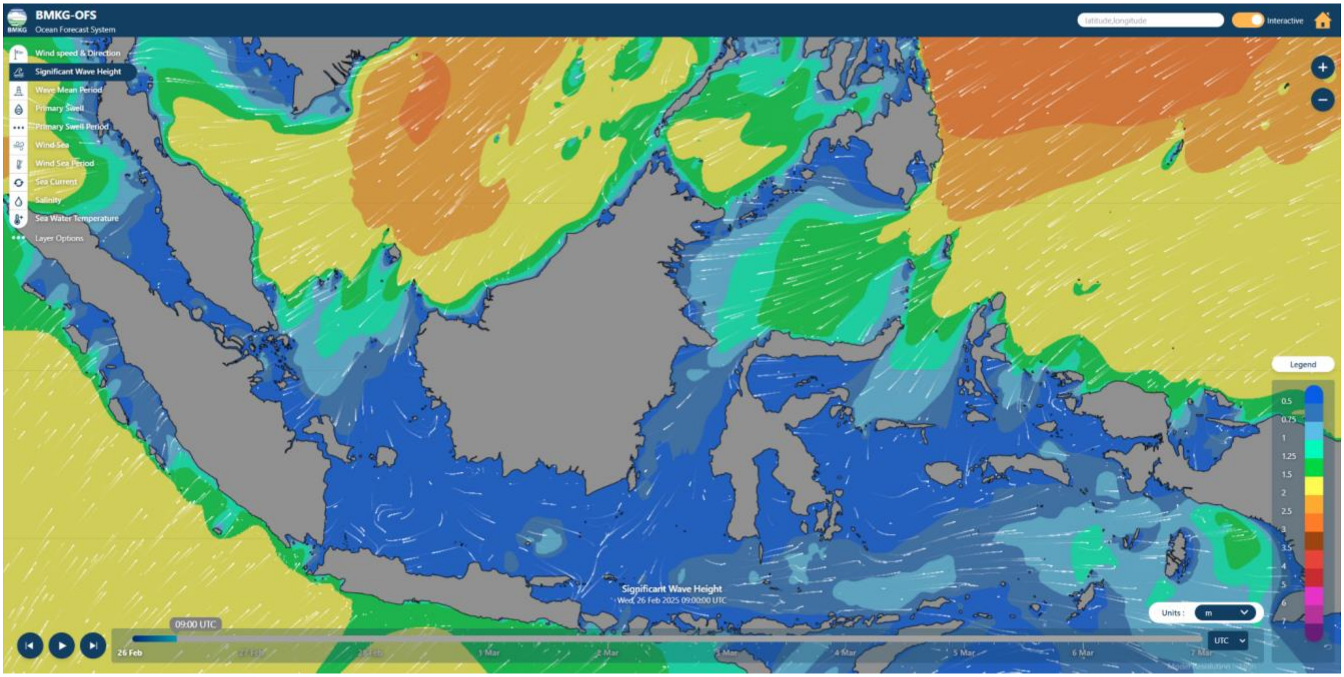


**Figure 3. Significant wave height derived from BKMG-OFS system (source: https://peta-maritim.bmkg.go.id/ofs/).**

The BMKG Ocean Forecast System (BMKG-OFS[6]) is an advanced forecasting system developed by Indonesia's Meteorological, Climatological, and Geophysical Agency (BMKG) to provide accurate and timely oceanographic information for the Indonesian seas (Figure 3). Launched in 2017, BMKG-OFS offers up to seven-day forecasts on various ocean parameters, including wind, waves, swell, currents, sea temperature, salinity, tides, sea level, and coastal inundation. The system utilizes the WaveWatchIII model to predict sea wave conditions and the FVCOM model to provide information on ocean currents, salinity, and sea temperature at various depths. There is a plan to improve the horizontal and vertical resolutions and an atmospheric-ocean-wave model.

Two major Korean institutes, the Korea Hydrographic and Oceanographic Agency (KHOA) and the Korea Institute of Ocean Science and Technology (KIOST) (whose details are provided in OceanPredict National Report, 2020) operate ocean forecasting systems to support various activities. Since 2012, KHOA has operated the Korea Ocean Observing and Forecasting System (KOOFS), consisting of nested ocean and atmospheric models with horizontal resolutions ranging from 4 km to 25 km. These models generate daily forecasting data covering regional, sub-regional, coastal, and port areas, with resolutions as fine as 0.1 km for major port areas. Since 2017, KIOST has also operated the Ocean Predictability Experiment for Marine environment (OPEM) (Jin et al. 2024), a regional ocean prediction system that provides weekly 10-day forecasts for the western North Pacific and has shown strong performance in simulating ocean conditions around Korea, particularly in response to extreme events such as typhoons and coastal upwelling. In 2020, a sub-coastal model with a resolution of ~300 m was

[6]https://maritim.bmkg.go.id/ofs

established, nested within the coastal model, which itself has a resolution of 1 km. In addition to these major oceanographic centers, some universities are also developing coastal forecasting systems. Kyusyu University in Japan operates several real-time ocean forecasting systems based on the Research Institute for 130 Applied Mechanics Ocean Model. This 3-dimensional ocean model is formulated in spherical coordinates with a horizontal resolution of approximately 1.5 km and features 114 vertical levels (Liu and Hirose, 2022). Its domain covers a rectangular region southwest of Japan, including part of the East China Sea shelf and the deep Okinawa Trough.

Bluelink[7] is an Australian ocean forecasting initiative established in 2003 through a collaboration between the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Bureau of Meteorology, and the Australian Department of Defence. It aims to develop and maintain world-leading global, regional, and littoral ocean forecast systems to support defence applications and provide a national ocean forecasting capability for Australia. Bluelink's operational system, the Ocean Modelling and Analysis Prediction System (OceanMAPS[8]), provides seven-day forecasts of ocean conditions, including currents, temperature, salinity, and sea level, on a near-global scale. These forecasts are crucial for various sectors, including maritime industries, defence applications, and climate research, aiding in decision-making and enhancing safety at sea (Brassington et al., 2023). The version 4 operational since 2022 uses the ensemble Kalman filter (EnKF).

## 4 Indian Ocean

Forecasting essential ocean variables from the Indian Seas comes with several hurdles compared to other regions due to the complex nature of the ocean dynamics and the specific characteristics of the Indian Ocean region such as the land-locked northern boundary. Major processes that make forecasting difficult in the region include the monsoon system, which brings abrupt and significant variability in wind patterns, precipitation, and oceanic processes. Seasonally reversing circulation patterns under the influence of monsoonal winds, coastal upwelling, and interactions with neighbouring ocean basins. Scarcity of comprehensive and high-quality observational data for initializing and validating ocean forecast models, particularly in remote areas and during extreme weather events. The Indian Seas have a complex coastline with extensive estuaries, deltas, and coral reef systems. Coastal processes, including tides, waves, and sediment transport, interact with ocean circulation and impact nearshore areas. Accurately representing these coastal processes in forecasting models poses challenges due to the high spatial variability and the need for high-resolution data and modelling techniques.

### 4.1 Regional systems

The Indian National Centre for Ocean Information Services (INCOIS) operates two regional ocean forecasting systems utilizing the Hybrid Coordinate Ocean Model (HYCOM) and the Regional Ocean Modelling System (ROMS). The regional

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[7]https://research.csiro.au/bluelink/global/forecast/
[8]http://www.bom.gov.au/marine/index.shtml

INCOIS-HYCOM has the highest resolution of approximately 6.9 km, followed by regional INCOIS-ROMS with approximately 9.2 km resolution. Regional INCOIS-HYCOM is forced with atmospheric variables from the NCEP-GFS and uses and assimilates Sea Surface Temperature (SST) data derived from the Advanced Very High-Resolution Radiometer (AVHRR) sensor, along track sea-level anomalies, in-situ profiles from various observing platforms using Tendral Statistical Interpolation Scheme (TSIS) Data Assimilation (DA) method (Srinivasan et al., 2022), taking boundary conditions from INCOIS GLOBAL HYCOM described earlier (Table 1).

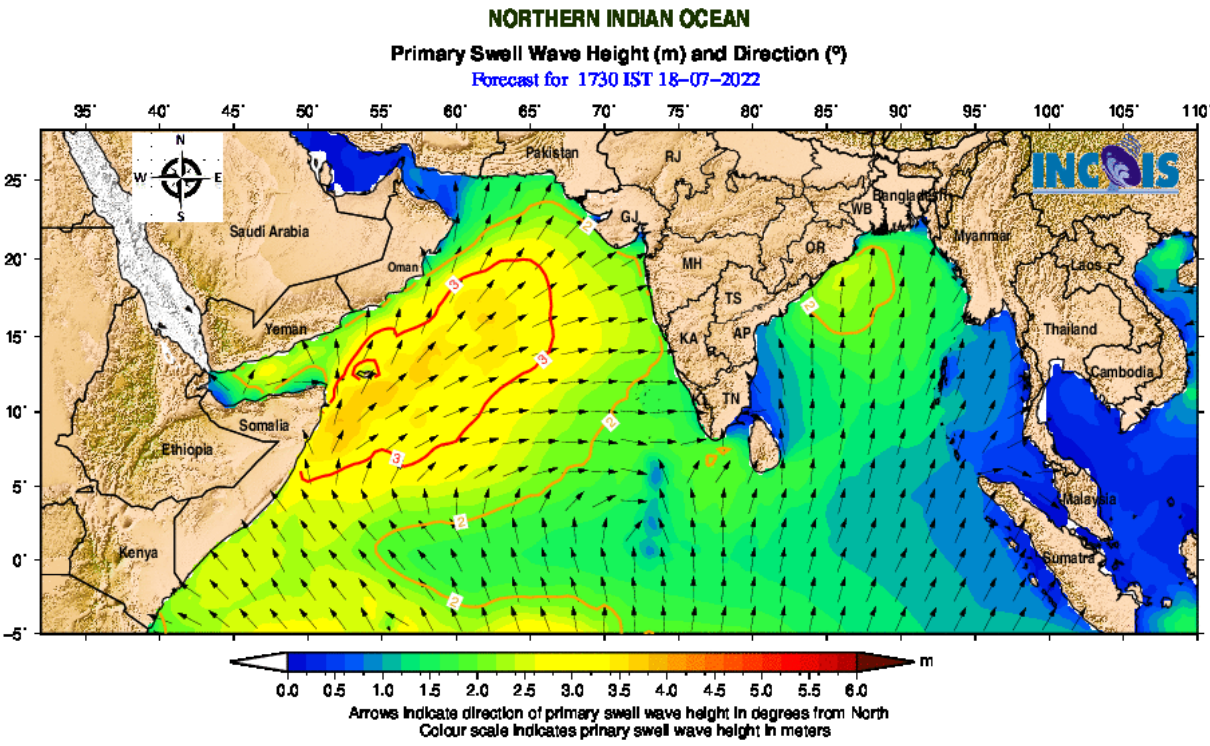


**Figure 4. Example of wave forecast produced by INCOIS.**

Regional ROMS model from INCOIS uses atmospheric forcing from the National Centre for Medium Range Weather Forecasting (NCMRWF[9]) Unified Model (NCUM) atmospheric system. It assimilates SST and vertical profiles of temperature and salinity from in-situ platforms using Local Ensemble Kalman Filter (LETKF) DA method. Data visualization and products from these models are available through web interface (https://incois.gov.in/portal/osf/osf.jsp) to users and data is made available to users on request.

[9]https://www.ncmrwf.gov.in/

INCOIS also provides operational wave forecasts through its integrated Indian Ocean Forecasting System (INDOFOS[10]). These forecasts are essential for maritime safety, navigation, and various ocean-based activities. INCOIS utilizes the third-generation wind-wave model WAVEWATCH III (Tolman, 2009) (Figure 4).

### 4.2 Coastal systems

INCOIS ROMS-Coastal is the only coastal model identified for the Indian Seas. It has approximately 2.3 km spatial resolution which is forced with the same NCUM atmospheric variables as in case of regional ROMS and does not assimilate any data but takes initial and boundary conditions from regional 9.2 km ROMS. Data visualization and products are made available through dedicated INCOIS web portal[11] and data is available to users on request.

## 5 African Seas

The African Seas can be subdivided into six regions, based on distinct ecosystem characteristics: the Canary Current Large Marine Ecosystem (LME), the Guinea Current LME, the Benguela Current LME, the Agulhas-Somali Current LME, the Red Sea LME and the Mediterranean Sea LME. Aside from the Mediterranean Sea LME, that will be discussed separately, an overview of the landscape with respect to operational ocean forecast services will be provided below. Operational ocean modelling is a developing field, with limited capacity in most parts of Africa. Operational services in these regions therefore depend largely on core global products and vary in levels of complexity, from disseminating locally relevant information via monthly bulletins to limited area forecast models that use global products at their boundaries. While various types of ocean forecast services exist to support national priorities, two consortia have been developed through Global Monitoring for Environment and Security (GMES[12]) and Africa to provide more regional support for marine and coastal operations. These are Marine and Coastal Operations for Southern Africa and the Indian Ocean (MarCOSIO[13]) and Marine and Coastal Areas Management in North and West Africa (MarCNoWA[14]). These platforms currently make use of global services for Earth Observations (EO) as well as marine forecast products that in some cases are optimized for local conditions.

### 5.1 Regional systems

There are a limited number of regional forecast systems optimized specifically for African Seas.

[10]https://incois.gov.in/portal/osf/osf_rimes/index.jsp
[11]https://incois.gov.in/portal/osf/osf.jsp
[12]https://gmes.rmc.africa/
[13]https://marcosio.org/
[14]https://geoportal.gmes.ug.edu.gh/#/

- The Iberia-Biscay-Ireland Marine Forecasting Centre (IBI-MFC[15]) Ocean Physics, Waves and Biogeochemistry Analysis and Forecast products, provided by the Copernicus Marine Service, are suitable for use by regional services in North and Northwest Africa.
- Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES[16]) has developed an integrated high resolution regional ocean forecasting system that encompasses the ocean regions of Madagascar, Mozambique and Seychelles.
- The Integrated Red Sea Model (iREDS-M1) has been developed by the King Abdullah University of Science and Technology in Saudi Arabia. Its atmospheric and ocean (wave and general circulation) models are running on an operational basis to provide short-range forecasts for the Red Sea (Hoteit et al., 2021).
- The South African Weather Service (SAWS[17]) provide regional wave, wave-current interaction and tide forecasts, downscaled from global services, none of which are assimilative (Barnes and Rautenbach, 2020). They also provide an empirically derived algorithm-based forecast of the sea-ice edge for METAREA VII (De Vos et al., 2021).
- The MarCNoWA focuses on delivering Earth Observation (EO) services on coastal and marine environments and fisheries:
    - Provision of potential fishing zone charts overlaid with vessel traffic,
    - Monitoring and forecasting oceanography variables,
    - Forecast of ocean conditions,
    - Oil spill monitoring,
    - Generation of coastal vulnerability indices, and Mapping of coastal habitats.

  Through a network of national stakeholders, regional fisheries and environmental bodies, academia, private sector and researchers, the project is to impact decision making in the beneficiary countries. It downscales Copernicus Marine products and provides forecasts (Forecasts - Global Monitoring for Environment and Security & Africa (rmc.africa).
- The forecasting system GCOAST[18], developed by HEREON, is implemented at regional scale for the western coast of Africa. The GCOAST[19] (Geesthacht Coupled cOAstal model SysTem) is built upon a flexible and comprehensive coupled model system integrating the most important key components of the regional and coastal systems and, additionally, allowing including information from observations. The operational modelling system is developed based on a downscaling approach from the Copernicus Marine GLO-MFC forecast products at 1/12º resolution,

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[15]https://marine.copernicus.eu/about/producers/ibi-mfc
[16]https://rimes.int/
[17]https://www.weathersa.co.za/
[18]https://www.hereon.de/institutes/coastal_systems_analysis_modeling/research/gcoast/
[19]https://www.hereon.de/institutes/coastal_systems_analysis_modeling/research/gcoast/index.php.en

focusing on the western African coast. The wind-wave model is based in WAM. The atmospheric forcing is taken from ECMWF.

### 5.2 Coastal systems

Operational ocean forecast services for African coasts include:

- The National Coastal Forecasting System for Mozambique (FEWS-INAM) provides 3-day ocean and meteorological forecasts in the form of daily bulletins and text messages to support operations at sea. It uses global NCEP-GFS data to provide meteorological and wave boundaries, and GLOSSIS[20] for the storm surge boundary conditions. The forecasts include wave information, tide and surge water levels and atmospheric weather information. This system was developed by a consortium, including Mozambique's Met Office INAM31, Deltares, UK Meteorological Office and the DNGRH.
- SAWS provides higher resolution wave forecasts, optimized for key coastal regions as well as storm surge forecasts. The information is disseminated on their web portal https://marine.weathersa.co.za/Forecasts_Home.html
- The SOMISANA[21] (A sustainable Ocean Modelling Initiative: a South African Approach) has developed two limited area downscaled bay-scale operational forecast systems for key areas around the South African coastline, which are: i) Algoa Bay (Figure 3) and the ii) Southwest Cape Coast. The models run daily and provide 5-day forecasts of currents, temperature and salinity through the water column. The models are forced by the GFS atmospheric forecasts at the surface and by the Global Ocean Analysis and Forecasts system provided by Copernicus Marine Service at the lateral boundaries. The model outputs can be explored at https://somisana.ac.za/ (Figure 5). The validation reports are available for the two operational forecast models.
- Coastal and fluvial flood forecasting developed in response to the extreme storm surge and flooding events on the Kwa-Zulu Natal coast of South Africa by Deltares and the local municipality[22]. The coastal (Delft3d) and fluvial (SWMM) models are run in forecast mode (Deflt-FEWS) every 6 hours and provide 3-day forecasts. As inputs they use global forecast services from the ECMWF and the NCEP.

[20]https://www.deltares.nl/en/expertise/projects/global-storm-surge-information-system-glossis
[21]https://somisana.ac.za/
[22]https://publications.deltares.nl/EP4040.pdf

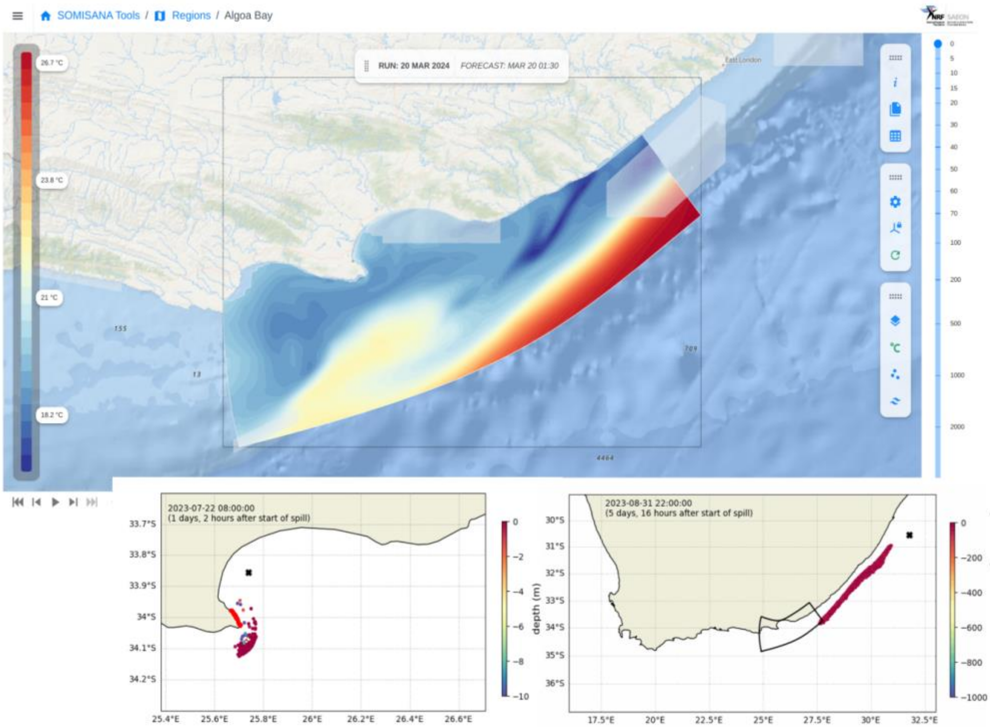


**Figure 5. The web-portal of the bay-scale forecast system developed by the SOMISANA team in South Africa. The web portal allows users to explore the variables as well as to scrutinize various depth-levels of the forecasts. The insets show the oil-spill tracking functionality, developed using the OpenDrift software, that allows for the seamless integration of the global and regional, bay-scale forecasts in tracking the spill.**

The coastal forecasting system developed in response to extreme storm surge, waves and flooding events along the eastern coast of Ghana utilizes advanced modelling techniques and global forecast services. The coastal model employed in this system is a flexible and modular modelling platform GCOAST (Geesthacht Coupled cOAstal model SysTem) for regional and coastal applications. The hydrodynamical model is based on SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model)[23], which is coupled with the wind wave model WWM. The coastal forecasting modelling platform ensures a flexible grid for the eastern coast of Ghana with a resolution ranging from 50 m in the estuaries up to 1 km. The system is designed to provide both hindcasts and forecasts. For hindcast simulations, it uses the GLORYS12 reanalysis (Global Ocean Physics Reanalysis, product ID: GLOBAL_REANALYSIS_PHY_001_030). For forecasts, it uses the GLO-MFC (product ID: GLOBAL_ANALYSIS_FORECAST_PHY_001_024). Atmospheric forcing is provided by the ECMWF operational forecast products. At the boundaries, the model is coupled to the Global Ocean Physics Reanalysis GLORYS[24] provided by the Copernicus Marine Service (as part of the GLO-MFC product catalogue) and produced by Mercator Ocean International. The

[23]https://ccrm.vims.edu/schismweb/
[24]https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description

coastal forecasting system incorporates tidal forcing from the Finite Element Solution 2014 (FES2014, Lyard et al., 2021) global ocean tide model, which provides tidal elevations and currents on a 1/16° grid and has demonstrated significant improvements over previous versions, particularly in coastal and shelf regions. This comprehensive approach ensures that stakeholders receive timely and accurate information to prepare and respond effectively to extreme events along the eastern coast of Ghana. In addition to its predictive capability, the system also supports environmental resilience. It integrates mangrove vegetation into the modelling platform to assess and promote nature-based solutions for coastal protection. This component enables the evaluation of scenarios in which mangrove cover is varied to estimate its potential to mitigate wave energy and reduce coastal erosion. The implementation builds on the findings of recent studies demonstrating the buffering role of mangroves against hydrodynamic forces in the coast of Ghana, contributing to sustainable coastal management strategies. These insights guide the design of adaptive coastal management strategies based on nature-based interventions (Jayson-Quashigah et al., 2025).

## 6 Mediterranean and Black Sea

The beginning of the 21st century can be considered the starting point of the Mediterranean and Black Seas operational forecasting services thanks to the favourable conjunction of several aspects:

- A general concept of operational oceanography was emerging worldwide.
- The advent of new ocean monitoring technologies allowing for multiplatform systems, including both in-situ monitoring and satellite remote sensing, that in addition to the development of internet network connections started providing open data with a near-real time availability (Tintorè et al., 2019).
- The development of numerical modelling and prediction systems gave rise in 2000 to the release of the first ocean forecast of the Mediterranean Forecasting System (MFS) which was providing regular and freely available 10-day predictions of the Mediterranean Sea dynamics with a spatial resolution of 7 km (Pinardi et al., 2003).
- The implementation of the first Black Sea nowcasting and forecasting systems which were developed during the first decade of 2000 in the framework of the ARENA[25] and of the EU FP6 ECOOP (European COastalshelf sea OPerational observing and forecasting system) projects.
- The Mediterranean scientific community started to get organized to establish a Mediterranean Operational Oceanography Network (MOON) which became in 2012 the Mediterranean Operational Network for the Global Ocean Observing System (MonGOOS[26]). Also, the Black Sea Community, within the Global Ocean Observing System, has been established into the Black Sea GOOS[27].

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[25] http://old.ims.metu.edu.tr/black_sea_goos/projects/arena.htm
[26] https://mongoos.eurogoos.eu/
[27] https://eurogoos.eu/black-sea/

In the following, some details on the services implemented in the Mediterranean and Black Sea are provided at regional scale, for the whole basins, and at coastal scale (here the global services are not considered since these basins have strongly regional dynamics and maintain a connection to the global ocean through the narrow strait of Gibraltar, in the case of the Mediterranean Sea, therefore, this section will only consider regional and coastal services).

### 6.1 Regional systems

There are a limited number of regional forecast systems optimized specifically for African Seas.

During the last decades, major developments have been undertaken to improve the operational forecasting systems of the Mediterranean and Black Seas, first in a pre-operational phase within MyOcean EU Projects leading to the Copernicus Marine Service since 2015. The Mediterranean (Med-MFC; Coppini et al., 2023) and the Black Sea (BS-MFC; Ciliberti et al., 2022) Monitoring and Forecasting Centres can be considered the core services for these regions (Figure 6).

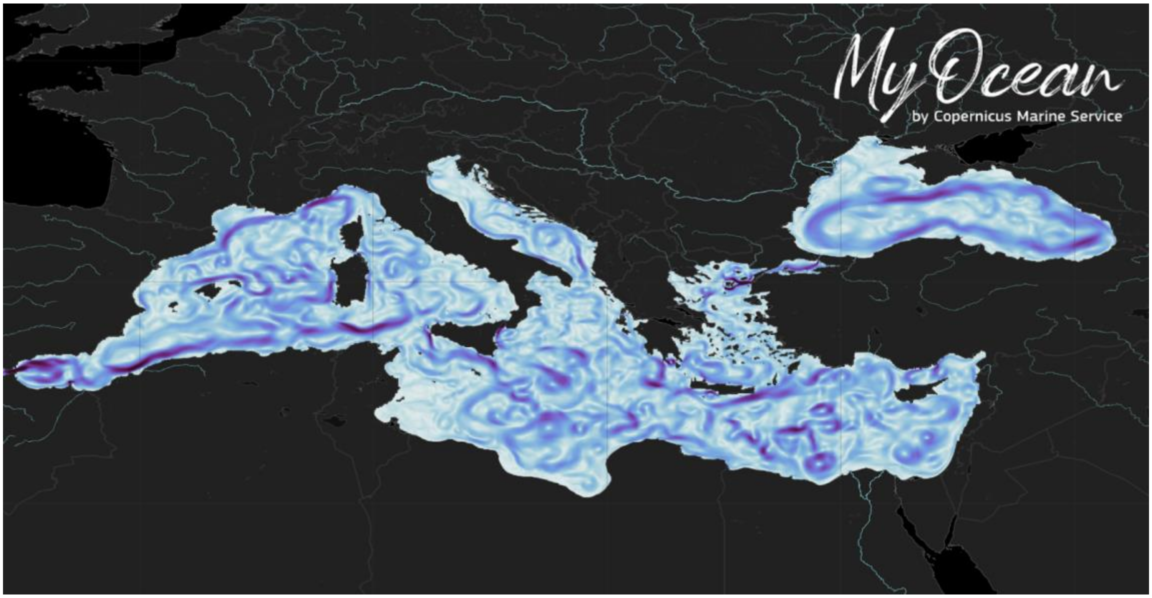


**Figure 6. Mediterranean and Black Sea Forecasting Systems sea surface currents visualization as provided by the Copernicus Marine Service.**

They provide, every day, 10 days forecast fields at around 4 and 2.5 km resolution, in the Mediterranean and Black Sea respectively, for the whole set of ocean essential variables including: currents, temperature, salinity, mixed layer thickness, sea level, wind waves, and biogeochemistry, which are freely available to any user (scientists, policy makers, entrepreneurs and ordinary citizens, from all over the world) though the Copernicus Marine Data Store. To support users, tailored services and training, adapted to different levels of expertise and familiarity with ocean data are also provided.

Three operational systems compose both the Med-MFC and the BS-MFC: the physical component which is based on NEMO (Madec et al., 2022) OGCM model, the wave component which is based on WAM (WAMDI Group, 1988) 3rd generation spectral model and the biogeochemical component which based on BFM (Vichi et al., 2020) and on BAMHBI (Gregoire et al., 2008; Capet et al., 2016) for the Mediterranean and Black Sea, respectively. The systems assimilate in situ and satellite data, including sea level anomaly along track altimetry data, significant wave height, sea surface temperature, and chlorophyll-a concentration, provided by the corresponding Copernicus Marine Thematic Assembly Centres, and are jointly and constantly improved following user's needs. These Mediterranean and Black Sea core services, by timely providing accurate boundary conditions, enables the implementation of higher resolution and relocatable forecasting systems in different areas and support the development of many downstream applications and services.

In addition to the abovementioned core services, other forecasting systems are implemented at regional scale such as:

- A high-resolution Mediterranean and Black Sea system based on MITGCM (Massachusetts Institute of Technology General Circulation Model, Marshall et al., 1997) described in Palma et al. (2020). The system includes tides, is resolved at a 2 km resolution (and higher resolution in specific areas) and is nested in the Med-MFC. This system has been used as a basis to develop a 1/16° model to assess present and future climate in the Mediterranean Sea focusing on sea-level change - MED16 (Sannino et al., 2022).
- The KASSANDRA[28] storm surge forecasting system for the Mediterranean and Black Seas which is based on the coupled hydrodynamic SHYFEM (Umgiesser et al., 2004) and wave (WaveWatchIII) models allowing for very high resolution in specific areas (Ferrarin et al., 2013).
- The MFS[29] developed at INGV (National Institute of Geophysics and Volcanology, Italy) with 1/16° resolution, based on NEMO and implementing a 3D variational data assimilation scheme (OceanVar, Dobricic and Pinardi, 2008).
- The physical and wave ocean system MITO (Napolitano et al., 2022) provides 5 days forecasts of the Mediterranean Sea circulation based on the MITGCM, is forced by the Copernicus Mediterranean physical and wave forecasting products to generate 5-day forecasts data at a horizontal resolution up to 1/48° degree.
- The POSEIDON[30] basin-scale Mediterranean forecasting system (~10 km resolution) ocean and ecosystem state, developed at HCMR (Hellenic Centre for Marine Research, Greece). This includes a hydrodynamic model, based on POM (Princeton Ocean Model, Blumberg and Mellor, 1987), which assimilates satellite and in situ data (Korres et al., 2007) and a biogeochemical model, based on ERSEM (European Regional Seas Ecosystem Model, Barretta et al., 1995; Kalaroni et al., 2020a, 2020b).
- The CYCOFOS wave forecasting system provides a 5 days forecast of the Mediterranean and the Black Sea (Zodiatis et al. 2018a) based on the WAM model and is forced by the SKIRON high frequency winds.

[28]http://kassandra.ve.ismar.cnr.it:8080/kassandra
[29]https://medforecast.bo.ingv.it/
[30]www.poseidon.hcmr.gr

### 6.2 Coastal systems

Several coastal systems are developed and implemented in the Mediterranean and Black Seas, not only for operational uses, but also for research purposes by a wide research community. These modelling systems generally make use of community models which are widely used by the scientific community for a diverse range of applications including the hydrodynamical, waves and biogeochemical marine components. In the following, several of them are illustrated providing main information and references for more details.

**HYDRODYNAMICS:**

- The IBI-MFC Physics Analysis and Forecasting System[31] provides operational analysis and forecasting data at 1/36º resolution implementing the NEMO model integrated with a data assimilation scheme SAM2, which allows a multivariate assimilation of sea surface temperature together with all available satellite sea level anomalies and in situ observations.
- The "Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria", SAMOA (Álvarez Fanjul et al., 2018; Sotillo et al., 2019; Garcia-Leon et al., 2022), provides operational downstream services and a significant number of high-resolution forecasting applications, based on Copernicus Marine forecasting services and Spanish Meteorological Agency (for atmospheric forecast), including 20 atmospheric models, 21 wave models and 31 circulation models. implements the ROMS (Regional Ocean Modeling System) model at a resolution of 350 to 70 m.
- The WMOP model (Juza et al., 2016; Mourre et al., 2018) based on ROMS is a downscaling of the Copernicus Mediterranean system with a spatial resolution of 2 km and covering the Western Mediterranean basin from the Strait of Gibraltar to the longitude of the Sardinia Channel. It is implemented by SOCIB (Balearic Islands Coastal Observing and Forecasting System) and is run operationally on a daily basis, producing 72-hour forecasts of ocean temperature, salinity, sea level and currents.
- A high-resolution numerical model, developed as part of an operational oceanography system in the frame of the "Sistema Autonomo de Medicion, Prediccion y Alerta en la Bahia de Algeciras" (SAMPA) project is implemented by Puertos Del Estado (Spain) providing operational ocean forecast data in the complex dynamical areas of the Gibraltar Strait and the Alboran Sea.
- The MARC (Modelling and Analyses for Coastal Research) and ILICO (Coastal Ocean and Nearshore Observation Research Infrastructure) are implemented using MARS3 model in the Bay of Biscay/English Channel/Northwestern Mediterranean Sea at 2.5 km horizontal resolution and nested in the Copernicus Global system.
- The Tyrrhenian and Sicily Channel Regional Model, TSCRM (Di Maio et al., 2016; Sorgente et al., 2016), is based on a regional implementation of POM at 2 km resolution and is nested into the Copernicus Mediterranean Analysis and Forecasting system.

[31]https://doi.org/10.48670/moi-00027

- The Southern Adriatic Northern Ionian coastal Forecasting System, SANIFS (Federico et al., 2017), is a coastal-ocean operational system based on the unstructured-grid finite-element 3D hydrodynamic SHYFEM model reaching a resolution of a few meters. It is a downscale of the Med-MFC physical product and provides short term forecast fields.
- The Aegean and Levantine Eddy Resolving Model, ALERMO (Korres and Lascaratos, 2003), is based on POM implemented at 1/48° resolution and nested into the Copernicus Mediterranean Analysis and Forecasting system.
- The Cyprus Coastal Ocean Forecasting and Observing System, CYCOFOS (Zodiatis et al., 2003, 2018b) is specifically developed to provide a sub-regional forecasting and observing system in the Eastern Mediterranean (including the Levantine Basin and the Aegean Sea). The latest system is forced by the Copernicus Med-MFC Physical forecasting system, implements POM at 2 km resolution to produce initial and open boundary conditions in specific locations.
- The TIRESIAS Adriatic forecasting system based on the unstructured grid 3D hydrodynamic model SHYFEM and representing the whole Adriatic Sea together with the lagoons of Marano-Grado, Venice and Po Delta (Ferrarin et al., 2019). It is a downscale of the Med-MFC physical product and provides 3-day forecast fields.

**WAVES:**

- The IBI-MFC Waves Analysis and Forecasting system (Toledano et al., 2022) is based on MF-WAM (Meteo-France WAM) implemented at 1/36º resolution and produces waves forecast in the Western part of the Mediterranean Sea twice a day.
- The SAPO[32] (Autonomous Wave Forecast System) based on WAM model is implemented at several Spanish Ports (Spain) with a horizon of 72 h forecast and it is nested within the PORTUS forecast system, an operational wave forecast for Spanish Port Authorities.
- WAMADR setup of ECMWF WAM is implemented by the Slovenian Environment Agency for Adriatic and Central Mediterranean domain with a horizon 72 hours and spatial resolution of 1.6 km. The model is forced by a hybrid ALADIN SI and ECMWF surface wind product and is running daily.
- Several coastal and local wave applications providing wave information near the harbours, as well as boundary conditions for specific wave agitation inside the port applications, are using the SWAN model (Booij et al., 1999).

BIOGEOCHEMISTRY:

- The IBI-MFC Biogeochemical Analysis and Forecasting System[33] is implemented using the PISCES (Aumont et al., 2015) model at 1/36º horizontal resolution.
- The Northern Adriatic Reanalysis and Forecasting system (NARF) and the CADEAU physical-biogeochemical reanalysis (Bruschi et al., 2021) are implementing the MITgcm-BFM coupled models in the Northern Adriatic Sea reaching up to 750 m with a further high-resolution (~125 m) nesting in the Gulf of Trieste (https://medeaf.ogs.it/got).

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[32]https://static.puertos.es/pred_simplificada/Sapo/d.corunia/sapoeng.html
[33]https://doi.org/10.48670/moi-00026

## 7 North-East Atlantic

Operational oceanography in European countries was mainly operated at a national level until the 1990s. In 1994, the European part of the Global Ocean Observing System (EuroGOOS[34]) was founded. It grouped these national endeavours into a network of European monitoring and forecasting systems and initiated several regional and thematic working groups to support specific developments. Since the early 1990s, the European Commission has been actively funding programmes to support ocean monitoring and forecasting through, for instance, its series of MyOcean projects (2009–2015) and its ongoing ambitious Copernicus Earth observation programme, which includes the Copernicus Marine Service component.

Due notably to the coordinating efforts provided by the Copernicus Marine Service over the last decade, the North-East Atlantic region is now well equipped in terms of operational marine forecasting services. Also, each segment of the North-East Atlantic coastline is included in at least one regional system, such that Global Forecast Services are seldomly used directly, except for the provision of boundary conditions to downstream forecast systems. An inventory of operational marine and coastal models around Europe was compiled out of a survey conducted in 2018–2019 among members of EuroGOOS and its related network of Regional Operational Oceanographic Systems (Capet et al., 2020), addressing the purposes, context, and technical specificities of operational ocean forecasts systems (OOFS). Here, we re-focus this analysis for the North-East Atlantic by excluding the Arctic, Mediterranean, and Black Sea basins from the original analysis. It should be noted that this inventory only includes OOFS actively reported to the survey and might therefore be incomplete. A further expansion of the North-East Atlantic OOFS inventory is expected from the OceanPrediction DCC Atlas.

Besides the three Copernicus Marine regional forecast services, the inventory includes 35 others regional OOFS and 32 coastal OOFS, arbitrarily identified as systems with a spatial resolution below 3 km, and longitudinal and latitudinal domain extent below 5 degrees.

[34]https://eurogoos.eu/

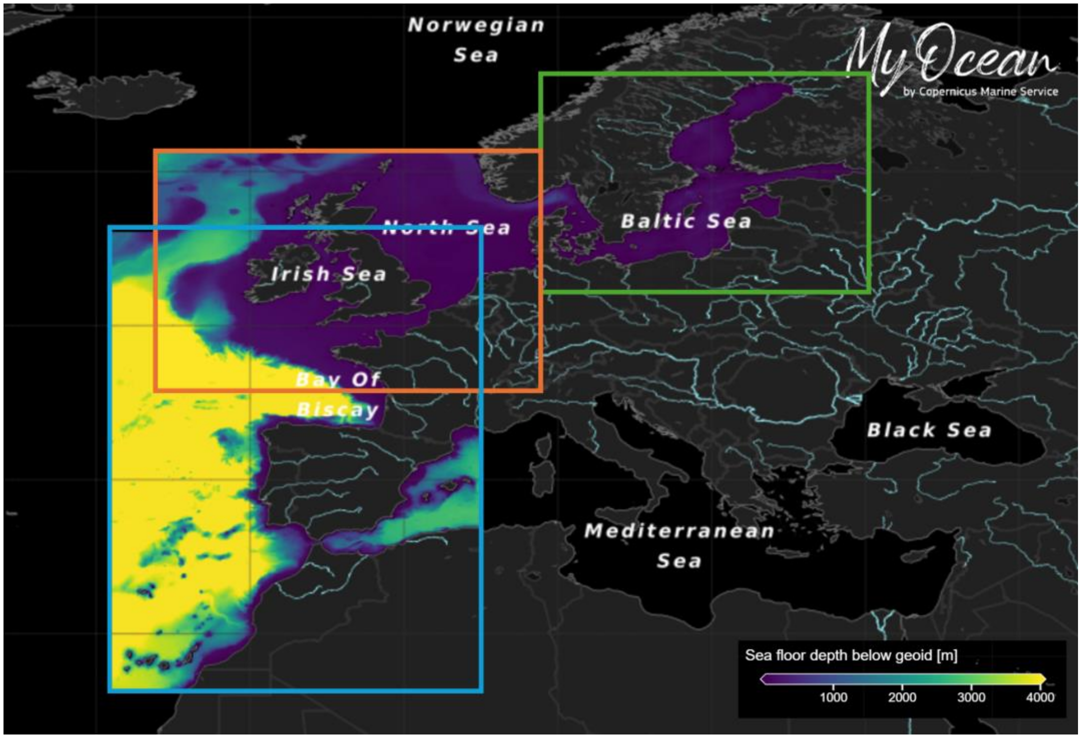


**Figure 7. The Copernicus Marine regional monitoring and forecasting centers operating in the area: IBI-MFC (in blue), NWS-MFC (in orange) and BAL-MFC (in green). The map shows bathymetry (m) and the composite regions obtained from the MyOcean Viewer (https://data.marine.copernicus.eu/viewer).**

### 7.1 Regional systems in the framework of the Copernicus Marine Service

The major marine core service for the North-East Atlantic is provided by the Copernicus Marine Service, and its three regional Monitoring Forecasting Centres (MFCs) dedicated to the Iberian-Biscay-Irish seas (IBI-MFC), European Northwestern Shelves (NWS-MFC[35]), and Baltic Sea (BAL-MFC[36]), respectively (Figure 7). In terms of modelling, each of these three MFCs is composed of dedicated components addressing ocean circulation (PHY), biogeochemistry (BGC), and wave dynamics (WAV). These systems operate under the coordinated umbrella of Copernicus Marine Service and therefore benefit from homogenized protocols in terms of operational data production, validation, documentation, and distribution (Le Traon, 2019). Products and related documentation can be accessed through the central Copernicus Marine Data Store, together with observational datasets including in-situ, remote sensing, and composite products for the Blue (physics and hydrodynamics), Green (biochemistry and biology), and White (sea-ice) ocean. Operational data delivery is provided through online data

[35]https://marine.copernicus.eu/about/producers/nws-mfc
[36]https://marine.copernicus.eu/about/producers/bal-mfc

selection tools and a variety of automatic protocols (e.g., Subset, FTP, WMTS), which effectively enables a number of operational downstream services to depend directly on those core services. A catalogue of such downstream usage and its potentialities is exposed on the Copernicus Marine Use-Cases portal[37].

### 7.2 Other regional systems

The 35 regional forecasts systems that are not operated by Copernicus Marine are mostly operated by national entities and provide data free of charge to relevant users in 71% of the cases. They address circulation (80% of the regional OOFS), wave dynamics (23%) and biogeochemistry (14%), as well as Lagrangian drift dynamics for the sake of oil spills and search and rescue services. 12 of these 35 systems report a dependence on the Copernicus Marine products (including GLO-MFC forecast products) in terms of open sea boundary conditions. Many of these systems (10) benefit from the SMHI e-Hype products to constrain river discharge. Regarding atmospheric conditions, a majority (22 regional OOFS) rely on Pan-European products (typically provided by ECMWF), but regional atmospheric products are also exploited, as qualitative operational products are provided by national agencies in most European countries.

### 7.3 Coastal systems

32 coastal OOFSs are reported in the EuroGOOS Coastal Working Group (CWG) inventory for the North Sea, Baltic Sea, and European shelves, addressing circulation (68% of the coastal OOFS), biogeochemistry (29%), and wave dynamics (4%). Again, these OOFSs are mostly operated by public entities (although this is recognized as a potential bias in the survey, as discussed in Capet et al. 2020) and provide, in the vast majority, forecast data freely accessible to relevant users.
Among coastal OOFS, the usage of land and atmospheric forcing data from specific national sources is much more common than for regional systems, indicating that adequate products are available at local scales. Besides, several coastal system operators rely on their own atmospheric or hydrology model to obtain adequate boundary conditions. One could highlight that 15 of the 35 reporting coastal OOFS provide forecasts at a spatial resolution below 500 m, at least in some parts of their domain. In general, such systems also consider fine bathymetry, with a minimal water depth of under 5m (Figure 8).
According to the survey, which was in almost all cases answered by model operators, OOFSs in the North-East Atlantic are relevant for marine safety, oil spills, and sea level monitoring concerns (Figure 9). Yet, the survey did not consider the extent to which provided information was effectively exploited by downstream operators. To a lesser extent, some systems address biochemical issues such as water quality, harmful algal blooms, or coastal eutrophication.

[37]https://marine.copernicus.eu/services/use-cases

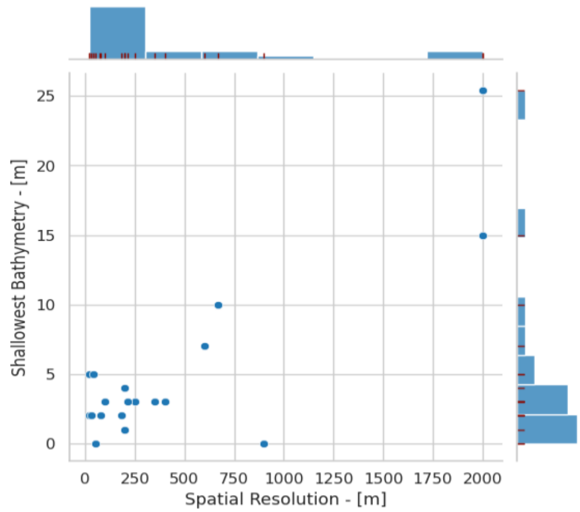


**Figure 8. Joint and marginal distribution of the minimal water depth and spatial grid resolution, for all North-East Atlantic coastal model domains illustrated in Figure 7.**

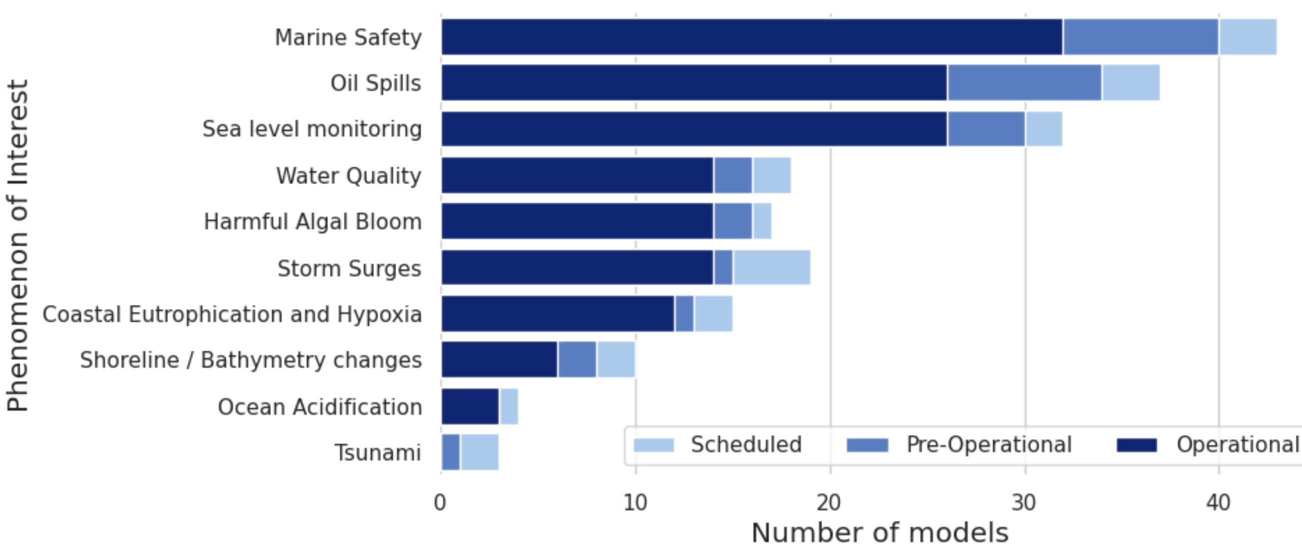


**Figure 9. Number of regional and coastal models considered by their providers to be relevant for a proposed set of downstream sectorial applications and phenomenon of interest. Based on the 2018-2019 EuroGOOS CWG survey (Capet et al. 2020).**

## 8 South and Central America

The development of short-range ocean forecasting systems in South and Central America is relatively recent with respect to other systems in Europe, North America and East Asia. They are very heterogeneous, reflecting their different needs, local observational systems, and infrastructure. Operational systems are present today in Argentina, Brazil, Chile, Colombia, Panama and Peru with focus on regional and basin scale domains in the West Pacific, South Atlantic and the Caribbean Sea, and tackling forecasts at short-term to seasonal timescales. All of them are rapidly evolving considering the outstanding scientific and technical knowledge conquered by the oceanographic global community and the permanent increase in computational resources. Some details about some of these systems are presented below.

**8.1 Regional systems**

In Brazil, a few regional (and coastal) forecast systems exist, considering the vast oceanic area under Brazilian jurisdiction (branded as Blue Amazon), which currently totalizes 4.4 million km2, approximately half of the Brazilian terrestrial area, with the possibility of reaching 5.7 million km2 in the future (Franz et al., 2021). The forecasting services results are not available for the public in general due to restrictions imposed by public-private partnerships and other constraints.

The first operational ocean forecast system with data assimilation in Brazil was implemented in the Brazilian Navy Hydrographic Center (CHM) in 2010 based on the Hybrid Coordinate Ocean Model (HYCOM) and on an optimal interpolation scheme, developed by the Oceanographic Modeling and Observation Network (REMO) (Lima et al., 2013). Since 2014, CHM-HYCOM forecasts was initialized by the REMO Ocean Data Assimilation System (RODAS) (Augusto Souza Tanajura et al., 2014; Tanajura et al., 2020) based on the optimal interpolation scheme, which can assimilate SST analysis, along-track or gridded sea level anomaly (SLA) and T/S vertical profiles. The ensemble members are chosen according to the assimilation day from a previous free run. The most recent CHM-HYCOM+RODAS configuration produces 5-day forecasts daily and encompasses the entire North, Equatorial, and South Atlantic with 1/12° horizontal resolution, to generate boundary conditions for a regional domain grid covering the METAREA-V (35.8°S-7°N, 20°W) with a horizontal resolution of 1/24°, both with 32 vertical hybrid layers. Other models are also employed operationally in CHM. ADCIRC is employed in Guanabara Bay, São Sebastião and Ilha Bela proximities and Sepetiba Bay, as well as in Santos and Paranaguá ports.

Regarding the Argentine Sea, the Modelling System for the Argentine Sea (MSAS) is used to model the barotropic component of the ocean state of the Southwestern Atlantic Continental Shelf. MSAS is based on the Coastal and Regional Ocean Community Model (CROCO[38]). Dinápoli et al. (2023) modified the source code to resolve the depth-averaged horizontal momentum and continuity equations, as well as consider spatially varying bottom friction. MSAS covers the Southwestern Atlantic Continental Shelf with a trapezoidal shape designed to avoid a significant number of land-points and ensure the regular spatial resolution of 8 km in both directions. Along the boundaries, the model is forced with tides and continental discharges, whereas in the interior of the domain, the ocean surface is forced by atmospheric pressure and surface wind stress (Dinápoli et al. 2020a, 2021, 2023). In addition, MSAS has been used to conduct several scientific studies on the barotropic nonlinear interactions in the region (Dinápoli et al., 2020b), the tidal resonance over the continental shelf (Dinápoli et al., 2024), and the genesis and dynamics of the storm surges along the coast (Alonso et al., 2024). Recently, the Asynchronous Ensemble Square

[38]http://www.croco-ocean.org

Root Filter (4DEnSRF, Sakov et al., 2010; Whitaker and Hamill, 2002) DA scheme was also incorporated as part of MSAS. The 4DEnSRF scheme is currently used to produce optimal initial conditions for the forecasts by assimilating tidal gauges and remote sensing observations. Because of the large and nonlinear impact of the wind uncertainty on the regional barotropic dynamics (Dinápoli et al., 2020a), an ensemble wind forecast is used. Dinápoli et al. (2023) used the 31-member ensemble from NCEP's Global Ensemble Forecast System, together with a set of perturbations of the tides. Since the atmospheric ensemble provides the wind field, rather than the wind stress, the former is estimated using the parameterization of Simionato et al. (2006). The incorporation of 4DEnSRF into MSAS forecasts, together an ensemble post-processing technique developed by Dinápoli and Simionato (2022), has improved the 96-hr forecasts by reducing the model bias and correcting the timing of the strong storm surges that affect the northern part of the Southwestern Atlantic Continental Shelf. It is important to mention that MSAS is running pre-operatively, and its solutions will be made public soon. Relevant developments have been achieved with regard to wind wave modelling. The numerical model WAVEWATCHIII was regionalized and validated with direct observations from a number of buoys scattered in the Southwestern Atlantic Continental Shelf.

In Peru, a large effort in climate modelling has been undertaken in the 2000s to develop sub seasonal forecasts and anticipate the significant socio-economic consequences of the El Niño Southern Oscillation (ENSO). The Geophysical Institute of Peru (IGP) has implemented recently in forecast mode a regional Earth System Model called IGP RESM-COW v1. This system released in December 2023 (Montes et al., 2023) is based on the CROCO ocean model (Debreu et al., 2012) coupled to the WRF atmospheric model through the OASIS coupler (Craig et al., 2017) and now serves as an additional forecasting tool for establishing the recommendations by the ENFEN (Estudio Nacional del Fenómeno El Niño), a governmental body responsible for monitoring, studying, and predicting the El Niño phenomenon and its impacts on the country. The IGP RESM-COW v1 has a horizontal resolution of 12km for the ocean component, and 30 km for the atmospheric component. The domain covers the entire Peruvian territory and part of the eastern Pacific. The current implementation takes as input the forecasts of the NOAA CFSv2 global climate model that have been corrected using a combination of Reanalysis data (GLORYS outputs and the NCEP Final Analysis (FNL) data), the climatological averages of the NCEP coupled forecast system model version 2 (CFSv2) and of a 22-years long simulation of the IGP RESM-COW v1 model. This allows forecasts of oceanic and atmospheric conditions to be made up to 7 months in advance (Segura et al., 2023). In addition, the Navy of Peru via the Dirección de Hidrografía y Navegación (Dihidronav) had implemented the WAVEWATCH III for representing the wave behaviour at the northern, central and southern off Peru with a prediction up to 5 days[39]. This product is available for the scientific community and public interested in understanding wave conditions (https://cpps-int.org/index.php/wave-watch). Operation systems are also under development at IMARPE (Instituto del Mar del Peru, https://www.gob.pe/imarpe) based on the CROCO system, which targets the aquaculture industry in Central Peru region (Arellano et al., 2023). IMARPE and IGP also produce forecasts of ocean conditions at regional scale (Equatorial Kelvin wave amplitude in the Eastern equatorial Pacific) at sub seasonal timescales based on shallow water models (Mosquera, 2014; Urbina and Mosquera, 2020).

[39]https://www.naylamp.dhn.mil.pe/dhn2/secciones/Pronosticos/pronosticosolas/Peru_Olas.php

As part as a 10-years long national program (CLAP), CEAZA (Center for Advanced Studies in Aride Zones) is also currently developing an operational forecast system for the Coquimbo region (central Chile) based on CROCO initialized by Mercator forecasts in order to inform the fishery industry and the public. The 7 days lead time forecasts are to be provided through a mobile app (https://app.ceaza.cl/) along with real-time observations (temperature, oxygen) from a buoy at Tongoy bay, a hot spot for the scallop aquaculture industry. The system is based on a CROCO configuration at 3 km resolution (Astudillo et al., 2019) and is coupled to a simple biogeochemical model (BioEBUS) that has been tuned and validated for the western coast of South America (Montes et al., 2014; Pizarro-Koth et al., 2019).

In Colombia, the Colombia's Marine Meteorological Service (SMM, in Spanish), hosted by the Dirección General Marítima (DIMAR) as part of the Ministry of Defense, has co-developed over the last 8 years the Integrated Forecast System for Comprehensive Maritime Security (SIPSEM, in Spanish; Urbano-Latorre et al., 2023). SIPSEM is an ecosystem of climate services (Goddard et al., 2020) for met-ocean applications, providing a suite of demand-driven and actionable information to ensure maritime safety and protect life at sea, while contributing to international regulations in the SOLAS, SAR, IALA, PIANC, IMO and WMO conventions. Focusing on the ocean component, SIPSEM uses CROCO involving different domains and nests, tailored for the different applications and coastal complexities. Application in regional scale in the Colombian Caribbean and Pacific employs a horizontal resolution equal to 9.16 km. Different CROCO forecasts systems are nested in global forecasts produced by HYCOM+NCODA, Copernicus Global Ocean Physics Analysis and Forecast, and US Global Navy Coastal Ocean Model. They are forced with the Weather and Research Forecast Model (WRF) with 27 km of horizontal resolution nested in GFS forecasts. For wind-generated wave prediction, daily WAVEWATCH III (Tolman et al., 2002) forecasts are used for local and regional areas with 3.7 km and 18.5 km and are periodically calibrated by fine-tuning various model-parameters to best represent the local observations. SWAN (Booij et al., 1999) is also used in nearshore and ports applications. Some key SIPSEM forecasts are publicly available via a web portal[40] developed targeting the general user.

### 8.2 Coastal systems

Regional to coastal operational models for the Brazilian Coast started to be developed in 2018 by the Centre for Marine Studies (CEM), from the Federal University of Paraná (UFPR), in collaboration with MARETEC, a research center of the Instituto Superior Técnico (IST – Universidade de Lisboa) from Portugal, through the application of the MOHID modelling system. This initiative, called Brazilian Sea Observatory (BSO), was initially supported by the User Uptake program from Copernicus Marine Service. In order to deliver high-resolution forecasts of the Brazilian coast, an operational modelling system was developed based on a downscaling approach from the GLO-MFC physical analysis and forecast system at 1/12º resolution, focusing on the south-eastern Brazilian shelf, including estuarine systems with important port activities and large environmental protection areas. Nowadays, the operational modelling system includes a model covering the south-eastern

[40]https://meteorologia.dimar.mil.co/

Brazilian shelf with a horizontal resolution of 1/24º, a model covering the coasts and adjacent shelf of the states of Santa Catarina, Paraná and São Paulo with a horizontal resolution of 1/60º, and high-resolution models (~120 m) for coastal systems (Florianópolis Bays, Babitonga Bay, and Paranaguá Estuarine Complex). The system is maintained by CEM/UFPR. Furthermore, an operational model was developed for the north of Brazil, encompassing the states of Amapá, Pará and Maranhão, and the Amazon River and Pará River estuaries, with a horizontal resolution ranging from 1/24º to 1/60º. The atmospheric forcing comes from the WRF model implemented by the Brazilian National Institute for Space Research (INPE) with 7 km of horizontal resolution. The operational models have a vertical discretization reaching about 1 m of resolution near the surface.

In Chile, efforts to implement operational forecasting systems were initially led by the Navy, with a focus on swell forecasting for the entire Chilean coast or some key sites. These efforts have recently diversified to address issues around marine resource management (industrial and artisanal fisheries, aquaculture) and extreme events prediction. They are mostly based on the use of the CROCO system. As part of the national program COPAS Coastal, University of Concepcion is currently developing a forecast coupled systems based on WRF[41], WAVEWATCHIII and CROCO to deliver 3 to 6 days forecasts of oceanic and weather conditions in the harbour of Coronel (378°S). The system is currently delivering operational products at 10 km resolution for the central Chile region (32°-38°S) in uncoupled mode (off-line) . It targets a resolution of 2km in fully coupled mode and extended coverage for the ports of Arica (17.5°S) and Antofagasta (21.5°S). The national Fisheries Development Institute (IFOP) has recently developed an operational system called MOSA for the South part of central Chile focused on the inland seas of the Los Lagos and Aysén regions. It provides forecasts at a 3-day lead time based on CROCO at 1.2 km. The atmospheric forcing is derived from a forecast run based on WRF at 3 km with open boundary conditions from the Global Forecast System (NCEP-GFS). Ocean boundary conditions are from GLO-MFC physical forecast products and river run-offs from 35 point sources are used based on the FLOW products. Forecasts are provided on-line.

Besides these initiatives funded by the academic and public sectors, there are some private companies that also provide ocean and atmospheric forecasting for port operations in Chile. Siprol SpA provides wave, wind, and waves forecasts. They also provide wave forecasting for Ecuador. Also, the company PRDW provides the Automated Wave Forecast System (AWFOS), with 3hrs to 10 days forecasting using a mathematical model coupled with a global wave model wave for deep waters. PRDW also provides forecasting for various sites in South American countries. Finally, the Port of San Antonio, the first port in Chile in terms of port operations, is using models from the Direction of Port Construction (Dirección Obras Portuarias) in collaboration with the National Institute of Hydraulic of Chile (https://www.dop.pelcam.io/about). The wind forecasting is provided by the San Antonio Port Company (EPSA). In all the above, it is unknown the model used, validation and details in model configuration. Coastal applications employ 1.83 km and port applications employ a grid with resolution varying from 750 m to 150 m. The daily prediction system also involves an ensemble of CROCO forecasts, continuously calibrated using a

[41]https://www.mmm.ucar.edu/models/wrf

pattern-based approach for the regional domain, and an additional local calibration for the coastal domains at higher resolutions.

## 9 North America

The marine environment characterizing North America – from the icy Arctic waters to the warm ones of the Gulf of Mexico – is deeply influenced by complex biogeochemical and physical processes. The coastal and open ocean regions of Canada, United States and Mexico need to be accurately forecasted to support Blue Economy, ecosystem management and disaster preparedness. This section provides an overview of existing ocean forecasting systems in the region from regional to coastal scale, highlighting prediction capabilities and main challenges they are expected to address.

### 9.1 Regional systems

Due to the strong economic impacts noted above, work on operational oceanography began in Canada in the late 20th century. The first system for the GSL included a baroclinic ice-ocean model at 5-km resolution (Saucier et al., 2003). Shortly thereafter, a similar system was implemented for Hudson Bay (Saucier et al., 2004). The GSL system was coupled to an atmospheric model (Pellerin et al., 2004) and later implemented at the Canadian Meteorological Centre (Smith et al., 2013a). A system was also put in place for the Grand Banks (Wu et al., 2010).

The developments of these foundational systems led to a recognition within the Government of Canada of the potential benefits that could be achieved through the development and implementation of a hierarchy of operational oceanographic systems and products. As a result, the Canadian Operational Network for Coupled Environmental PredicTion Systems (CONCEPTS[42]) initiative was put in place between Environment Canada, the Department of Fisheries and Oceans and the Department of National Defence (Smith et al., 2013b; https://science.gc.ca/site/science/en/concepts). The CONCEPTS initiative developed strong ties to Mercator Ocean to accelerate the development of a Canadian ocean assimilation capacity to complement the expertise in ice-ocean modelling and atmosphere-ice data assimilation. This effort produced the Global Ice Ocean Prediction System (GIOPS[43]; Smith et al., 2016) which paved the way for the first-ever operational global medium-range fully-coupled atmosphere-ice-ocean forecasting system (Smith et al., 2018). Subsequently, a 16-day and monthly ensemble coupled forecasting system was implemented (Peterson et al., 2022) based on the same ice-ocean model configuration and initialized using GIOPS analyses.

In 2017, the Canadian Government agreed to take responsibility for METAREA regions 17 & 18 of the Global Marine Distress and Safety System. This required the dissemination of warnings for the weather and ice hazards over a pie-shaped region stretching from the Bering Strait to North of Greenland and up to the north pole. As a result, the Regional Ice Ocean Prediction

[42]https://science.gc.ca/site/science/en/concepts
[43]https://science.gc.ca/site/science/en/concepts/prediction-systems/global-ice-ocean-prediction-system-giops

System (RIOPS[44]; Smith et al., 2018) was developed to produce analyses and forecasts over METAREA 17 & 18 regions, but also including all Canadian coastal waters from 44°N in the Pacific Ocean through the Arctic and down to 26°N in the Atlantic Ocean. RIOPS evolved from an initially ice-only system (Buehner et al., 2016; Lemieux et al., 2016) based on the development of the CREG12 ocean configuration (Dupont et al., 2015).

As part of the Year of Polar Prediction (YOPP; Goessling et al. 2016) from 2017-2019, a pan-Arctic high-resolution coupled atmosphere-ocean system was developed and run operationally to support Arctic field campaigns and operational activities. This system, called the Canadian Arctic Prediction System (CAPS; Casati et al., 2023), used the RIOPS ice-ocean configuration coupled to a 2.5-km resolution atmospheric model to produce 48-hr forecasts. This system was retired following YOPP, but is now in the process of being reinstalled in 2025.

In the United States, the National Oceanic and Atmospheric Administration (NOAA) and the Department of the Navy jointly pushed for the development of robust operational forecasting systems from regional to coastal scale to provide support safe maritime operations, including tropical cyclone predictions, search and rescue, response to marine emergencies and operations near the marginal sea-ice zone (Davidson et al., 2021).

NOAA operates different ocean forecasting systems to support monitoring in the US region. The (Atlantic) Real-Time Ocean Forecast System (RTOFS[45]) is a regional data-assimilating nowcast-forecast system operated by the NCEP, based on the HYCOM model. The grid is telescopic and orthogonal, varying from approximately 4-5 km near the US East Coast to almost 17 km near West Africa (Figure 10) (Mehra and Rivin, 2010). The system runs on a daily basis with a 24 hours assimilation hindcast and produces 2D ocean forecasts on hourly basis for sea surface height (m), sea surface salinity (PSU), sea surface temperature (Celsius), sea surface currents (m/s) and mixed layer thickness (m) and 3D ocean forecasts over 40 pressure levels up to 5 days (120 hours) for salinity (PSU), temperature (Celsius), currents (m/s), mixed layer thickness (m).

[44]https://science.gc.ca/site/science/en/concepts/prediction-systems/regional-ice-ocean-prediction-system-riops
[45]https://polar.ncep.noaa.gov/ofs/download.shtml

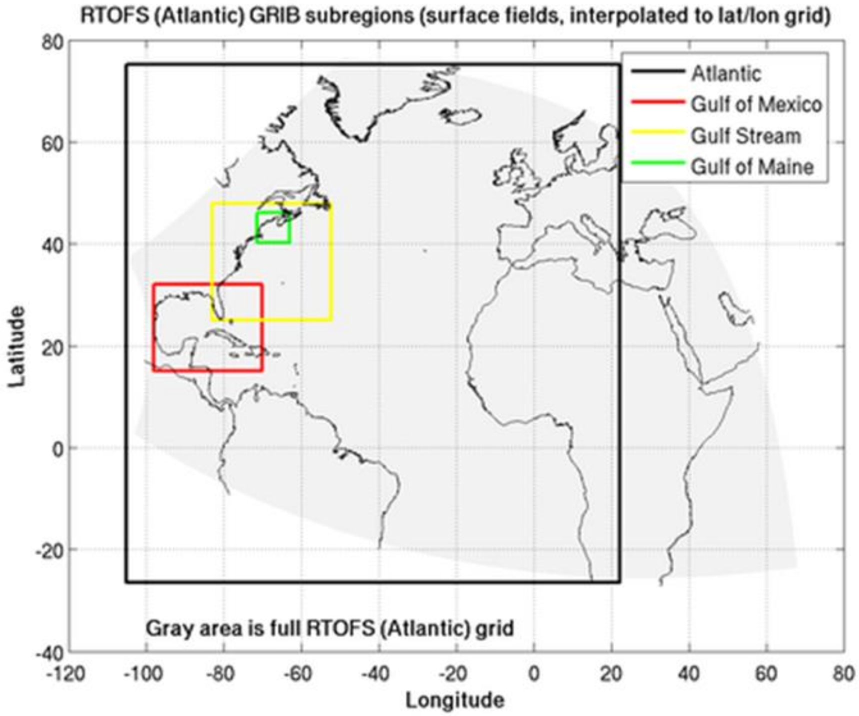


**Figure 10. RTOFS high resolution oceanic model spatial domain including subregions (source: https://ocean.weather.gov/index.php).**

The NOAA Ocean Prediction Center (OPC), as part of NCEP, maintains and develops 5 operational desks that run in 10 hours shift for the Atlantic Regional, the Atlantic High Seas, the Pacific Regional, the Pacific High Seas and for the Outlook. They are devoted to producing gridded forecasts for hazards, winds, waves, weather and ice accretion, focusing only to US exclusive economic zones. Products for the Atlantic and the Pacific Regional desks include 24 hours surface and wind/wave forecasts, while the Atlantic and Pacific High Seas desks produce analysis two times per shift and 48 hours forecasts. The Pacific High Seas includes Alaska and Arctic projections in addition to forecast products. The Outlook desk provides medium range forecasts for 72 and 96 hours (source: https://www.weather.gov/marine/). In such a context, specific operational services are operated to provide valuable support for any meteo-marine emergency occurring in the region.

The operational Hurricane Analysis and Forecast System (HAFS[46]) of NCEP provides a reliable and skillful model on Tropical Cyclone track and intensity since 2023. It is forced by atmospheric fields provided by the NOAA Global Forecast System (NCEP-GFS) and uses as ocean initial/boundary conditions the RTOFS fields. HAFS is configured with two storm-centric domains with nominal horizontal resolutions of 6 km and 2 km, respectively.

[46]https://www.aoml.noaa.gov/hurricane-analysis-and-forecast-system/

NOAA Tide Predictions[47] system provides tidal forecasts in specific stations located in the West Coast, the East Coast, in the Gulf Coast, in the Pacific and Caribbean Islands. Queries are allowed on hourly, 15- and 6 minutes frequencies

The Instituto de Ciencias de la Atmósfera y Cambio Climático at the Universidad Nacional Autónoma de México (UNAM) has developed and currently maintains a regional forecast system that includes meteorology (for Mexico and adjacent regions), ocean circulation (currently the Gulf of Mexico), waves (global and regional with higher resolution), sea level, tides and storm surge, volcanic ash dispersion, oil spill dispersion in the ocean and fire smoke dispersion.

The different components of the system began to work in different years, and UNAM has tried to keep them working every day of the year, being successful at more than 99% of the time. This system of models is the base of other systems that are developed for other institutions such as the Mexican National Weather Service, PEMEX (e.g., the national oil company), and CENAPRED, which is part of the national civil system protection. Table 2 summarizes the main characteristics of systems operating in Mexico.

[47]https://tidesandcurrents.noaa.gov/tide_predictions.html

**Table 2. Principal characteristics of the core services operating in Mexico.**

| Component | Model | Domain | Resolution | Start date |
|---|---|---|---|---|
| Meteorology | WRF-UNAM[48] | 122.5ºW to 75.0ºW and 0.0ºN to 37.0ºN | 15 km / 5 km | 2007 |
| Ocean Circulation | HYCOM-UNAM[49] | 18.0ºN to 32.0ºN and 98.0ºW to 76.0ºW | 1/25º | 2014 |
| Waves | WWIII-UNAM | 15.0ºN to 38.0ºN and 100.0ºW to 75.0ºW | 15 km | 2009 |
| Tides and Storm Surge | ADCIRC-UNAM[50] | Two Domains: a) one for the Gulf of Mexico and b) the other for the Eastern tropical Pacific of México | Variable, with higher resolution near the shore line where is 500m | 2017 |
| Volcanic Ash Dispersion | FALL3D-WRF-UNAM[51] | For the Popocatepetl Volcano: 101.0ºW to 96.0ºW and 17.0ºN to 21.0ºN | 5 km | 2017 |
| Oil Spill Module | Quetzal-UNAM[52] | Can be applied in regions that have meteorology and oceanic data. Mainly the Gulf of Mexico | Almost continuous since it is Lagrangian | 2023 |
| Smoke module | Tezcatlipoca-UNAM[53] | Can be applied in any region with wind data from model (at least same as our WRF) | Almost continuous since it is Lagrangian | 2023 |

[48] https://pronosticos.atmosfera.unam.mx/operativo/index.php/meteorologia
[49] https://pronosticos.atmosfera.unam.mx/hycom/index.php
[50] https://pronosticos.atmosfera.unam.mx/operativo/index.php/marea-de-tormenta
[51] https://pronosticos.atmosfera.unam.mx/operativo/index.php/dispersion-de-cenizas
[52] https://pronosticos.atmosfera.unam.mx/hycom/index.php/modelacion-de-derrames-de-petroleo
[53] https://pronosticos.atmosfera.unam.mx:20001/

Operational ocean circulation model for Gulf of Mexico circulation operates at a resolution of 1/25º of a degree using HYCOM, generating hourly output on a daily basis. The model utilizes a distinct bathymetry and coastline compared to the HYCOM Consortium's model. Surface forcings are provided by our WRF model, while global HYCOM data are used for open boundary conditions. Initial conditions are derived from global HYCOM, with a restart from the previous forecast if necessary. We are currently developing an in-house data assimilation technique for improving initial conditions. UNAM employs the WaveWatchIII model on a structured grid for wave forecasting. A global wave model, driven by the Global Forecast System at a 1-degree resolution, provides boundary conditions for two regional models: one covering the Gulf of Mexico and the northwestern Caribbean Sea, and the other covering the Eastern Tropical Pacific. Both regional models operate at a 15 km resolution, utilizing hourly surface forcings from our WRF model. Storm surge forecasting is conducted using the ADCIRC model on a non-structured mesh in two domains: one covering the Gulf of Mexico and the northwestern Caribbean Sea, and the other covering the Eastern Tropical Pacific. The model resolution along the coastline of these domains is at least 500 m resolution. Open boundary conditions are provided by 8 tide components from the TP9 model, with surface forcings obtained from our WRF model. The model produces forecasts for up to 120 hours, with hourly outputs.

### 9.2 Coastal systems

In the fourth phase of growth in Canadian operational oceanography there was a recognition of the need for improved coastal surface currents to support environmental emergency response (e.g. for oil spills) and for electronic marine navigation (e-Nav) as part of the Government of Canada's Ocean Protection Plan (OPP). Supported by OPP funding, the CONCEPTS initiative developed a 2-km Coastal Ice-Ocean Prediction System (CIOPS) for the east and west coasts (Paquin et al., 2024). The ocean analyses for CIOPS are now used to initialize coupled atmosphere-ice-ocean forecasts covering the Great Lakes and Canadian East Coast as part of the Water Cycle Prediction System (Durnford et al., 2018). As a result, the coupled GSL system was retired in 2021.

A cascade of grids was then used to provide boundary conditions from CIOPS for six Port Ocean Prediction Systems (POPS). The POPS domains include Kitimat, Vancouver Harbour and Fraser River on the west coast and Canso, St. John harbour and the St. Lawrence Estuary on the east coast (DFO, 2025). These systems provide high-resolution surface currents for electronic navigation, with resolutions down to 20 m (Paquin et al., 2020).

While various biogeochemical modelling applications have been made for Canadian coastal regions, these have yet to culminate in an organized operational service. Discussions are underway regarding the specific needs and how these can be met (Lavoie et al., 2025).

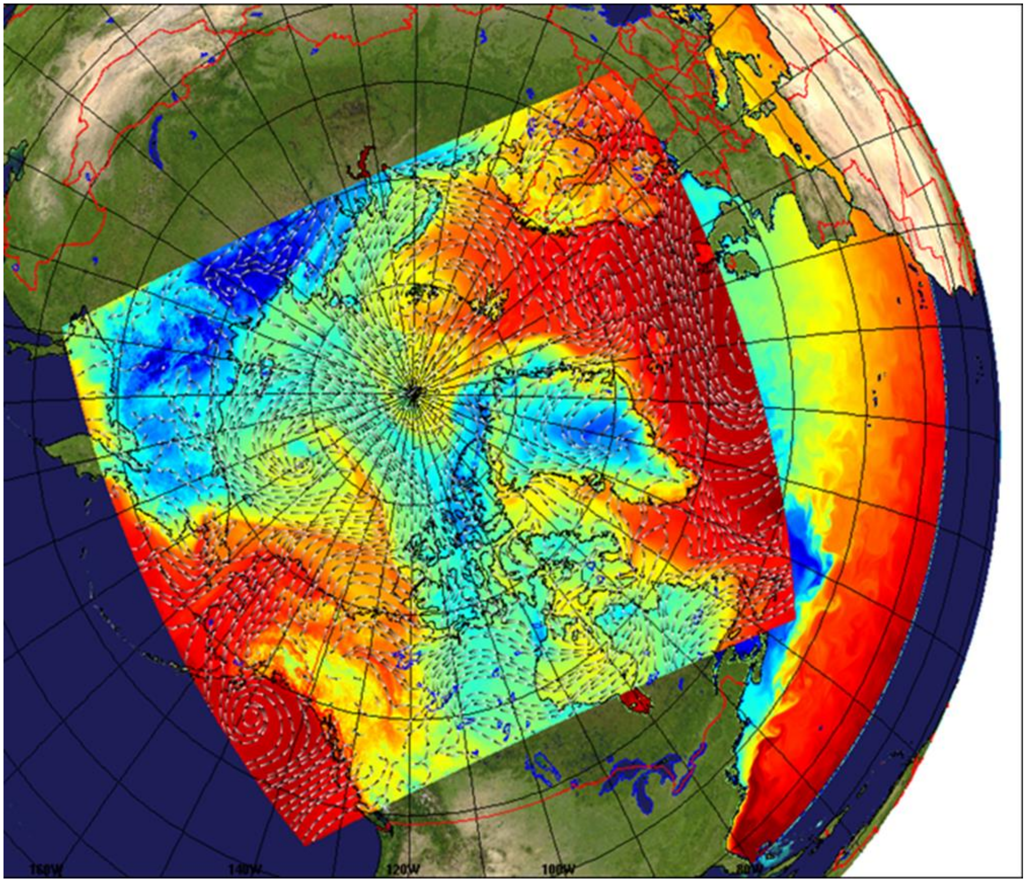


**Figure 11. Model domain used for the CONCEPTS Canadian Arctic Prediction System (CAPS) which includes a 3-km resolution atmospheric configuration coupled to the RIOPS ice-ocean configuration. The atmospheric surface temperature and winds are overlaid on a map of sea surface temperature for RIOPS. Note that the ice-ocean domain has been extended to include the North Pacific Ocean down to 44N.**

The operational CONCEPTS systems products are available through the Meteorological Service of Canada Open Data platform (Data list /Liste des données - MSC Open Data / Données ouvertes du SMC), including direct data access and geospatial web services (Figure 11). Data are also available for download and visualization from the Ocean Navigator[54].

At the coastal scale, many OOFS are operated by NOAA/NCEP to support safety and navigation.

- In the Pacific:
    - West Coast Operational Forecast System (WCOFS[55]) is a high-resolution forecasting system that operates in the West Coast, providing 3 to 7 days forecasts for sea level, currents, temperature and salinity. The system is based on ROMS, implemented in a spatial domain that stretches along the western coast of the North American continent from 24ºN (Mexico) to 54ºN (British Columbia), with an horizontal resolution that

[54]https://www.oceannavigator.ca/public/

[55]https://tidesandcurrents.noaa.gov/ofs/wcofs/wcofs.html

varies from 2 to 4 km. It assimilates SST, sea surface currents (SSUV), SLA using the 4DVAR scheme (Kurapov et al., 2017).

    - Cook Inlet Operational Forecast System (CIOFS[56]) generates water levels, water temperature and salinity, winds nowcast and forecast up to 48 hours, 4 times per day. The system is based on ROMS and uses orthogonal grid with horizontal resolution that spans from 10 m within the estuaries and navigation channels to 3.5 km near offshore waters.
    - Salish Sea and Columbia River Operational Forecast System (SSCOFS[57]) provides nowcast and forecast for water levels, currents, water temperature and salinity, incorporating river forcing from available observations and tidal forcing. The model has an unstructured triangular grid. The resolution varies from ~ 100 m along the shoreline to 500 m in deeper parts of Puget Sound and the Georgia Basin, and increases to 10,000 m over the continental shelf. Resolution in the Columbia River varies between 100 and 200 m.
    - San Francisco Bay Operational Forecast System (SFBOFS[58]) is based on FVCOM for providing a nowcast and forecast of water levels, temperature and salinity in the San Francisco Bay and in the San Francisco Bay Entrance. The grid has a minimum depth of 0.2 m and maximum depth of 106.8 m. Grid resolution ranges from 3.9 km on the open ocean boundary to approximately 100 m near the coast, indicating the flexibility of the grid size based on bathymetry from the deep ocean to the coast. Additionally, the higher resolution along the navigational channels within the bay, from approximately 100 m to 10 m, provides detailed current features.

- In the Great Lakes, 4 FVCOM-based operational systems are available:
    - Lake Erie Operational Forecast System (LEOFS[59]) at horizontal resolution from 400 m to 4 km, with higher resolution along the shoreline and in the shallow western basin and coarser resolution for the open waters in the mid and eastern basins.
    - Lake Michigan and Huron Operational Forecast System (LMHOFS[60]), at horizontal resolution from 50 m to 2.5 km, with higher resolution along the shoreline and in the shallow western basin and coarser resolution for the open waters in both lakes.
    - Lake Ontario Operational Forecast System (LHOFS[61]), at horizontal resolution from 200 m to 2.5 km, with higher resolution along the shoreline.

[56]https://tidesandcurrents.noaa.gov/ofs/ciofs/ciofs.html
[57]https://tidesandcurrents.noaa.gov/ofs/dev/sscofs/sscofs_info.html
[58]https://tidesandcurrents.noaa.gov/ofs/sfbofs/sfbofs_info.html
[59]https://tidesandcurrents.noaa.gov/ofs/leofs/leofs_info.html
[60]https://tidesandcurrents.noaa.gov/ofs/lmhofs/lmhofs_info.html
[61]https://tidesandcurrents.noaa.gov/ofs/loofs/loofs_info.html

    - Lake Superior Operational Forecast System (LSOFS[62]), at horizontal resolution 200 m to 2.5 km, with higher resolution along the shoreline.
- In the Gulf of Mexico:
    - Northern Gulf of Mexico Operational Forecast System (NGOFS2[63]), based on FVCOM with resolution from 10 km on the open ocean to approximately 600 m near the coast. Additional refinement of the grid is provided within the bays from 45 m to 300 m. The system runs 4 times per day providing a forecast up to 48 hours.
    - Tampa Bay Operational Forecast System (TBOFS[64]), based on ROMS, with a resolution from 100 m to 1.2 km. It has been designed to include the whole Tampa Bay and the shelf to properly represent the dynamics at the entrance to the bay.
- In the Atlantic, 5 ROMS-based systems provide nowcasts and forecasts up to 48 hours 4 times per day:
    - Chesapeake Bay Operational Forecast System (CBOFS[65]), with a resolution spanning from 30 m to 4 km.
    - Delaware Bay Operational Forecast System (DBOFS[66]), with a resolution ranging from 100 m up to 3 km.
    - Gulf of Maine Operational Forecast System (GoMOFS[67]), at 700 m resolution approximately, with forecast horizon up to 72 hours.
    - New York and New Jersey Operational Forecast System (NYOFS[68]), that provides water levels and currents using a grid with horizontal resolution from 5 m to 7.5 km.
    - St. John's River Operational Forecast System (SJROFS[69]), with horizontal resolution from 80 m to 4 km.

Academia, governmental institutes and the private sector cooperate for improving numerical modelling, engaging the enterprise to accelerate scientific research and excellence in the US coastal predictions. Examples of coastal systems that are developed in the US include:

- Coastal Storm Modeling System (CoSMoS), developed by United States Geological Survey (USGS): it is a storm-induced coastal flooding, erosion, and cliff failures system for the North-Central Coast, San Francisco Bay, Southern California and the Central California coast (Barnard et al., 2014).
- West Florida Coastal Ocean Model (WFCOM), developed by the USF College of Marine Science in Florida: it is an unstructured grid FVCOM in the Eastern Gulf of Mexico that provides water level (storm surge) forecasts as well as surface currents and surface salinity (Zheng and Weisberg, 2012).

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[62]https://tidesandcurrents.noaa.gov/ofs/lsofs/lsofs_info.html
[63]https://tidesandcurrents.noaa.gov/ofs/ngofs2/ngofs.html
[64]https://tidesandcurrents.noaa.gov/ofs/tbofs/tbofs_info.html
[65]https://tidesandcurrents.noaa.gov/ofs/cbofs/cbofs_info.html
[66]https://tidesandcurrents.noaa.gov/ofs/dbofs/dbofs_info.html
[67]https://tidesandcurrents.noaa.gov/ofs/gomofs/gomofs_info.html
[68]https://tidesandcurrents.noaa.gov/ofs/nyofs/nyofs.html
[69]https://tidesandcurrents.noaa.gov/ofs/sjofs/sjofs_info.html

- South Florida Hybrid Coordinate Ocean Model (SoFLA-HYCOM) Shelf Circulation, developed by University of Miami: its resolution spans from 1/25° to 2 m close to the coast and includes shelf areas, shallow embayment, and the deep Straits of Florida (between Florida and Cuba) (Kourafalou et al., 2009).
- LiveOcean, developed by the University of Washington - Coastal Modelling Group, mainly used for research applications. It provides 3 days forecasts of currents, temperature, salinity and many biogeochemical variables in the US Pacific Northwest. The model horizontal resolution is 500 m in the Salish Sea and near the Washington coast, growing to 3 km at the offshore boundaries (source: https://faculty.washington.edu/pmacc/LO/LiveOcean.html).

## 10 Arctic Region

In contrast to lower-latitude models, Arctic Ocean forecast models are focused on simulating the correct sea ice conditions, with the ocean below the mixed layer being of secondary importance on short time scales. However, this situation is expected to change with the retreating ice cover in the Arctic Ocean driving impacts on ocean ecosystems and increased activity across the Arctic region. There are 10 global models that are used for Arctic forecasting. There are also several regional models available, and a handful of coastal models. Most models with Arctic forecasts are from national institutes that either represent large centres with dominant global forecasting platforms, have a large amount of Arctic research, or have an interest in maintaining a model due to having a border with the Arctic.

Given the focus around sea ice, there are several similarities across all forecasting systems, regardless of the domain. Firstly, all models must have a sea ice component. Almost all models use CICE as their sea ice model, with multiple sea ice thickness categories. The Arctic Ice Ocean Prediction System (ArcIOPS) uses the sea ice model in MITgcm, while VENUS uses the ice component of POM, the GLO-MFC physical analysis and forecasting system uses LIM2 and the Met Office FOAM and coupled models use CICE currently but will move to using SI3 in the future. The FIO-COM10 model uses the SIS sea ice model. The majority of forecasting models with an ocean component use HYCOM or NEMO for their ocean model; the exceptions are ArcIOPS (MITgcm), NOAA PSL (POP2), and FIO-COM10 (MOM5). Most of the models have an ice-ocean coupling and use an atmospheric forcing that has been created for a weather forecast; examples are those from ECMWF, the Regional Deterministic Prediction System, and NAVGEM. Four of the models identified - one regional model (NOAA PSL CAFS) and three global models (NAVY-ESPC, Met Office coupled system and ECMWF) - are fully coupled to the atmosphere.

Another similarity between all models is the output variables. Those models with an ocean component provide standard variables (temperature and salinity) with most also providing velocities and sea surface height. Each model also provides the standard sea ice variables (sea ice concentration, sea ice thickness, and sea ice velocities) as outputs, generally at hourly resolution. Additionally, all models use some form of data assimilation over the initial part of the simulation before the forecast begins (usually one day). This is an important part of Arctic forecasting given that the ability to forecast sea ice depends heavily on the initial conditions. Most models assimilate the standard ocean variables (SST, sea surface salinity SSS, SSH and temperature and salinity profiles) and sea ice concentration.

Finally, perhaps one of the most important considerations for users is whether the data is readily available and easily downloadable. The requirement for this varies greatly depending on the user, but those needing information on ships in the Arctic, for example, will need quick access across potentially low bandwidth. All models related to Copernicus Marine Service (neXtSIM-F, TOPAZ54, Arctic Ocean Biogeochemistry Analysis and Forecast, and Global Ocean Physical Analysis and Forecasting by MOi) are available to download for free from the Copernicus Marine website, and there is a visualization tool on the information page. Most other modelling systems have data for download and a visualization, although sometimes in different places; these are the Barents-2.5km, NOAA ice drift, NOAA PSL, RIOPS, GIOPS, GOFS3.1, and RTOFS. The systems from DMI and GOFS16 have a web page displaying the forecasts. As noted in Section 9, the CONCEPTS systems (GIOPS, RIOPS, CIOPS) are available through the Meteorological Service of Canada Open Data platform (Data list /Liste des données - MSC Open Data / Données ouvertes du SMC), including direct data access and geospatial web services. Data are also available for download and visualization from the Ocean Navigator (https://www.oceannavigator.ca/public/). The ArcIOPS, FIO-COM10 and NAVY-ESPC systems are well-documented in the literature, but it is hard to find a website that states where/if downloading is available. The latter suggests some outputs are available for researchers if they register for a login, but it is not stated how other users can access the data. Similarly, it is difficult to find information on how to access outputs from the Met Office FOAM and its coupled data assimilation counterpart. For the global ECMWF model, some data is available, but users must pay for other variables.

There are strong crossovers between the global and regional models, and therefore specific details of both domains (covering the full Arctic) are provided below together, followed by the Arctic coastal forecasts.

### 10.1 Regional systems

Several institutions are operating regional services in the Arctic

- The Arctic Ice-Ocean Prediction System ArcIOPS[70] (Liang et al., 2019) is managed by the Danish Meteorological Institute (DMI). It employs the HYCOM-CICE model, covering the North Atlantic and Arctic Oceans with a horizontal resolution of approximately 4-5 km in the Arctic and up to 10 km further south. The system is forced by ECMWF weather forecasts and provides 144-hour forecasts twice daily at 00 and 12 UTC.
- The Danish Meteorological Institute (DMI) operates an ocean forecasting system utilizing the HYCOM-CICE model[71] (Ponsoni et al., 2023). This coupled ocean and sea-ice model covers the Atlantic Ocean north of approximately 15°S and the Arctic Ocean, including Greenlandic waters. The system features a horizontal resolution ranging from about 4-5 km in the Arctic regions to approximately 10 km further south. It is forced by atmospheric

[70]http://www.oceanguide.org.cn/IceIndexHome/ThicknessIce
[71]https://ocean.dmi.dk/models/hycom.uk.php

data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and produces 144-hour forecasts twice daily, at 00 and 12 UTC.

- The neXtSIM-F[72] forecasting system (Williams et al., 2021) is a stand-alone sea ice model developed by the Nansen Environmental and Remote Sensing Centre (NERSC). It utilizes the neXtSIM model, forced by the TOPAZ ocean forecast and ECMWF atmospheric forecasts. The system assimilates OSI SAF[73] sea ice concentration products daily, adjusting initial conditions and applying compensating heat fluxes to enhance forecast accuracy.
- The National Institute of Polar Research (NIPR[74]) in Japan provides Arctic Sea ice forecasts through its Arctic Sea Ice Information Centre. These forecasts are disseminated periodically, with reports typically released in May, July, August, and October each year. The May to August reports focus on predicting the opening dates of Arctic sea routes and the sea ice distribution through September, while the October report forecasts sea ice distribution for the period of sea ice extension from October onward.
- The NOAA Physical Sciences Laboratory (PSL[75]) operates the Coupled Arctic Forecast System (CAFS), an experimental sea ice forecasting model. CAFS is a fully coupled ice-ocean-atmosphere model adapted from the Regional Arctic System Model (RASM) and includes components such as the Weather Research and Forecasting (WRF) atmospheric model, the Parallel Ocean Program (POP) ocean model, the Los Alamos Community Ice Model (CICE), and the Community Land Model (CLM). All components run at a horizontal resolution of 10 km. The system is initialized with the NOAA Global Forecast System (NCEP-GFS) analysis and Advanced Microwave Scanning Radiometer 2 (AMSR2) sea ice concentrations. CAFS produces 10-day sea ice forecasts daily, with outputs posted online at 2 UTC
- The Regional Ice-Ocean Prediction System (RIOPS[76]; Smith et al., 2021) is operated by the Canadian Meteorological Centre (CMC). It employs the Nucleus for European Modelling of the Ocean (NEMO) coupled with the Los Alamos Sea Ice Model (CICE). The system is forced by atmospheric data from the Global Deterministic Prediction System (GDPS) and provides a forecast horizon of up to 48 hours. The model domain covers the North Pacific Ocean from 44N, the complete Arctic Ocean and the North Atlantic down to 26ºN with a horizontal resolution of approximately 3-4 km over the Arctic Ocean. A fully-coupled forecast system called the Canadian Arctic Prediction System, that uses RIOPS and a pan-Arctic atmospheric configuration at 2.5 km resolution is currently being reinstated (see Section 8 for details) following its retirement in 2021.
- The TOPAZ4 system[77] is maintained by the NERSC. It utilizes the HYCOM model coupled with the Ensemble Kalman Filter for data assimilation. The system is forced by atmospheric data from the ECMWF and provides a

[72]https://data.marine.copernicus.eu/product/ARCTIC_ANALYSISFORECAST_PHY_ICE_002_011/description
[73]https://osi-saf.eumetsat.int/
[74]https://www.nipr.ac.jp/sea_ice/e/forecast/
[75]https://psl.noaa.gov/forecasts/seaice/about.html
[76]https://science.gc.ca/eic/site/063.nsf/eng/h_97620.html
[77]https://data.marine.copernicus.eu/product/ARCTIC_ANALYSISFORECAST_PHY_002_001/description

forecast horizon of up to 10 days. The model domain encompasses the North Atlantic and Arctic Oceans with a horizontal resolution of approximately 12.5 km.

- The VENUS forecasting system (Yamaguchi, 2013) is operated by the Norwegian Meteorological Institute (MET Norway). It employs the NEMO ocean model coupled with the LIM3 sea ice model. The system is forced by atmospheric data from the AROME-Arctic weather prediction model and provides a forecast horizon of up to 66 hours. The model domain covers the Barents Sea and adjacent Arctic waters with a horizontal resolution of 4 km.

There are several characteristics to be highlighted in these systems:

- Most models are either coupled ice-ocean or coupled ice-ocean-atmosphere models. However, there are a few exceptions to this. The regional model neXtSIM-F is a standalone sea ice model that uses TOPAZ54 ocean and ECMWF atmosphere forecast forcings, and therefore only outputs sea ice variables. It is the only model to use a Lagrangian framework and a non-standard rheology. TOPAZ54 is the only model that has a version with a coupling to ECOSMO, a biogeochemical model, and additionally assimilates chlorophyll for input to this.
- The lowest resolution of the provided models is the regional ArcIOPS, at around 18 km. The resolution of the regional models is comparable to the global models.
- Apart from RIOPS, which runs for 84 hours at hourly resolution, most models covering the full Arctic domain provide outputs for five to ten days, ranging from hourly output to daily output. NOAA ice drift and NAVY-ESPC provide forecasts for up to 16 days, the latter can also give information for up to 45 days but at a lower resolution.
- Some models also provide additional sea ice variables; RIOPS, for example, and its global equivalent GIOPS, provide ice pressure, while TOPAZ54 provides sea ice type, albedo, and snow depth. The VENUS models include wave information. TOPAZ54 running with ECOSMO outputs several biogeochemical variables including dissolved inorganic carbon, oxygen, nitrate, chlorophyll, and phytoplankton.
- The VENUS model is unique in that it provides map-based forecasts for aiding ship navigation (generally in support of research cruises) and is deployed on demand rather than running continuously.

### 10.2 Coastal systems

There are a few coastal models available in the Arctic region.

- The coastal version of the DMI forecast model covers the Greenland region at 4-5 km resolution and uses HYCOM-CICE like its regional version. It produces forecasts up to 144 hours ahead and is updated twice a day.
- The Barents-2.5km model[78] covers the Barents Sea and Svalbard region (Röhrs et al., 2023). The ROMS model is run at a spatial resolution of 2.5 km with an Arctic-specific atmospheric forcing, AROME-Arctic, providing forecasts up to 66 hours ahead, and is updated every 6 hours.

[78]https://ocean.met.no/models

- The "storm surge" service[79] is a ROMS model run in barotropic mode, covering the northern North Atlantic, Barents Sea, and Svalbard up to the entrance to the Arctic Basin. It uses the MEPS 2.5km atmospheric model for outputs, providing forecasts for 120 hours updated every 6 hours. Its main purpose is to simulate sea level and storm conditions.
- The CIOPS-E system (Paquin et al., 2024) is a 1/36° (25km) resolution NEMO-CICE coupled model that is forced by the High-Resolution Deterministic Prediction System atmospheric forcing and covers the East coast of Canada. During its assimilation, it also uses RADARSAT satellite images. In addition to standard sea ice and ocean variables, it outputs snow depth on sea ice and ice pressure at hourly frequency for the following 48 hours.

## 11 Conclusions

The global landscape of ocean forecasting services demonstrates a solid and mature foundation, particularly through the widespread availability and reliability of global models. These models provide essential large-scale information and underpin the functionality of numerous regional and coastal systems. However, despite their robustness, global models often lack the resolution required to address the finer-scale dynamics necessary for many localized applications, particularly in coastal zones and regions with complex bathymetry or strong human-ocean interactions.

A clear disparity exists in the coverage and capabilities of regional and coastal forecasting systems. Some areas, particularly in developed regions, benefit from dense, high-resolution services, while others—especially in less-resourced coastal regions—remain underrepresented or underserved. Furthermore, while physical and wave modeling systems have seen significant advancements and widespread implementation, biogeochemical models lag behind in both availability and operational maturity. This gap limits our ability to provide comprehensive ecosystem forecasts and hampers decision-making related to marine biodiversity, fisheries, and water quality.

Looking forward, emerging technologies such as Artificial Intelligence (AI, Heimbach et al., 2025) hold immense potential to bridge these gaps. AI techniques can enhance model downscaling, fill data-sparse regions, and optimize system performance, thereby reducing disparities in forecasting capacities globally. However, while technological solutions are making impressive advancements and can have a great impact in the implementation of the ocean value chain (Ciliberti and Coro, 2024; Porter and Heimbach, 2025) they remain insufficient on their own.. Continued efforts in community building, knowledge sharing, and capacity development are paramount. Initiatives such as those promoted under the United Nations Decade of Ocean Science for Sustainable Development provide critical platforms for fostering collaboration, developing shared tools, and ensuring equitable access to forecasting capabilities across all regions.

[79]https://ocean.met.no/models

In this context, the OceanPrediction DCC Architecture (Alvarez et al., 2024a) offers a significant opportunity to promote the development of robust ocean forecasting services worldwide. By providing a structured, modular framework for the development of forecasting systems, it facilitates interoperability, scalability, and the integration of these systems. The concept of Operational Readiness Level for Ocean Forecasting (Alvarez et al., 2024b), developed within the DCC framework, will contribute to the quality of the system by supporting the application of Best Practices. These tools, when combined, have the potential to accelerate the creation of new regional and coastal systems, while simultaneously enhancing the quality, reliability, and user engagement of existing ones.

By aligning technological innovation with inclusive community-driven approaches, the global ocean forecasting community can work towards a more comprehensive, high-resolution, and biogeochemically informed future, better serving society's growing and diverse needs.

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**Competing interests**

The authors declare that they have no conflict of interest.

**Authors contribution**

MC designed, supervised, and validated the overall manuscript. All authors contributed to writing and revising the paper. Section 2 was additionally revised by EAF. EAF and MC conceptualized and wrote Section 1. WM wrote Section 3, SJ wrote Section 4, JV and JS wrote Section 5, EC wrote Section 6, and AC and GES co-wrote Section 7. BD, MD, IM, DN, CGS, CAST, and MC collaborated on Section 8, while GCS, PH, and SC contributed to Section 9. HR wrote Section 10. EAF and MC also contributed to the Conclusions.

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