

A description of existing Operational Ocean Forecasting Services around the Globe

Mauro Cirano¹, Enrique Alvarez-Fanjul², Arthur Capet³, Stefania Ciliberti⁴, Emanuela Clementi⁵, Boris Dewitte⁶, Matias Dinápoli⁷, Ghada El Serafy⁸, Patrick Hogan⁹, Sudheer Joseph¹⁰, Yasumasa Miyazawa¹¹, Ivonne Montes¹², Diego Narvaez¹³, Heather Regan¹⁴, Claudia G. Simionato⁷, Gregory C. Smith¹⁵, Joanna Staneva¹⁶, Clemente A. S. Tanajura¹⁷, Pramod Thupaki¹⁸, Claudia Urbano-Latorre¹⁹, Jennifer Veitch²⁰

¹Departamento de Meteorologia, Instituto de Geociências, Universidade Federal do Rio de Janeiro (UFRJ), Brazil

²Mercator Ocean International, Toulouse, France

³ECOMOD, Royal Belgian Institutes of Natural Sciences, Brussels, Belgium

⁴Nologin Oceanic Weather Systems, Santiago de Compostela, Spain

⁵Euro-Mediterranean Center on Climate Change, Bologna, Italy

⁶Centro de Estudios Avanzados en Zonas Aridas, La Serena, Chile

⁷CIMA, Instituto Universidad de Buenos Aires UBA, Argentina

⁸Data Science and Water Quality, Deltares, Delft, the Netherlands

⁹NOAA, National Centers for Environment Information, Stennis Space Center, Hancock County, Mississippi, United States

¹⁰Indian National Centre for Ocean Information Services (INCOIS), Pragathi Nagar, Nizampet, Hyderabad, Telangana 500090, India

¹¹Japan Agency for Marine-Earth Science and Technology, Kanagawa, Japan

¹²Instituto Geofísico del Perú, Lima - Perú

¹³Universidad de Concepcion, Concepcion, Chile

¹⁴Nansen Environmental and Remote Sensing Center, Bergen, Norway

¹⁵Meteorological Research Division, Environment and Climate Change Canada, Canada

¹⁶Helmholtz-Zentrum hereon GmbH, Geesthacht, Germany

¹⁷Federal University of Bahia (UFBA), Brazil

¹⁸Hakai Institute, Canada

¹⁹Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe DIMAR, Bolivar, Colombia

²⁰Egagasini Node, South African Environmental Observation Network (SAEON), Cape Town, South Africa

Correspondence to: Mauro Cirano (mauro.cirano@igeo.ufrj.br)

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

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

44 **1 Introduction**

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

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

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

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

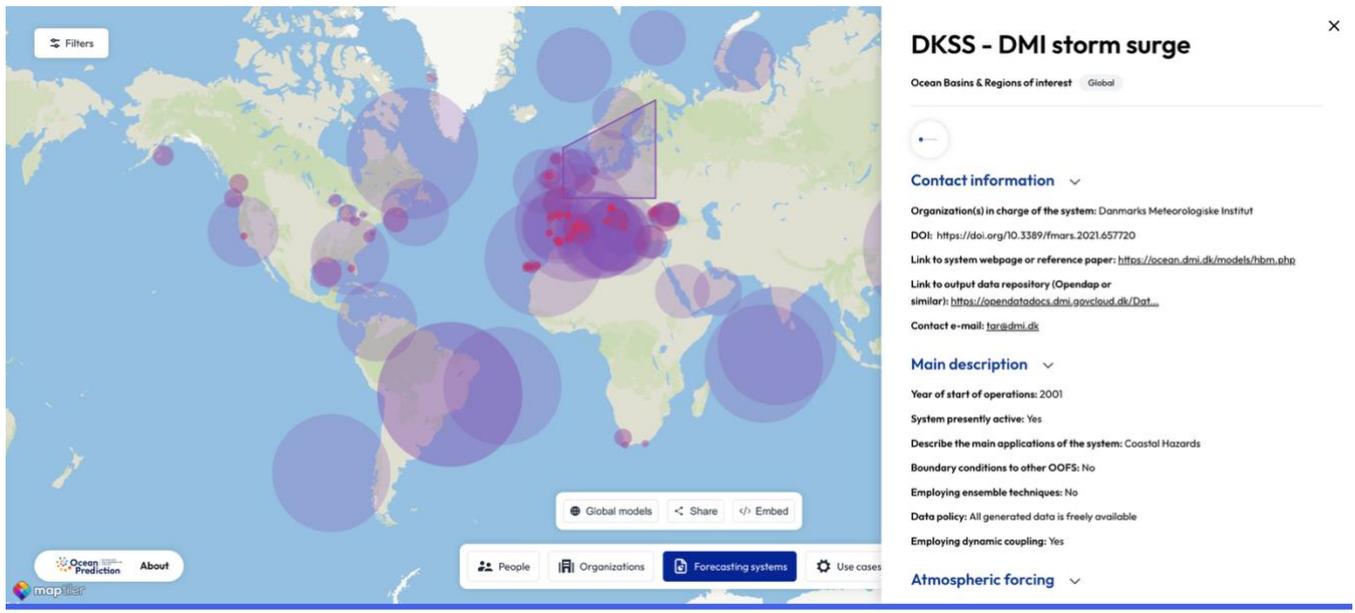
61 The main inventory for operational ocean forecasting services existing today is the Atlas of these services hosted on the
62 OceanPrediction Decade Collaborative Centre (DCC) web site¹. In this already growing inventory more than 150 worldwide
63 systems are described in detail showing a comprehensive picture of the activity in this field (Figure 1).

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

66 **2 Global Ocean Forecasting Services**

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

¹<https://www.unoceanprediction.org/en/atlas>



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

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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.

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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.

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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).

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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.

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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

90 The data sources employed for assimilation change from one system to another, being the used ones ARGO profiles, satellite
91 altimetry, satellite Sea Surface Temperature (SST), buoy data, drifters, XBT, and gliders. Six systems are using dynamic
92 coupling between different models or model components. All systems, but one, are providing the data to third parties, directly

93 or after a specific request. Surprisingly, almost half of the systems declare not being validated operationally. The forecast
94 horizon is usually between 5 to 10 days.

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

- 100 • Mauritius (using Copernicus Marine GLO-MFC products): the Mauritius Oceanography Institute provides a web
101 portal² (affiliated with GMES and Africa) that outputs a regional subset of global sea-state forecasts. Monthly
102 bulletins are targeted at users from the marine and fisheries realm for monitoring purposes and are a source of
103 information for researchers and the scientific community.
- 104 • Kenya (using INCOIS services): the Kenyan Meteorological Department provides daily and weekly marine forecast
105 bulletins (<https://meteo.go.ke/>).
- 106 • Mozambique (using INCOIS services): Integrated Ocean and Information System for Mozambique, developed by the
107 INCOIS project Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES).
- 108 • South Africa (using NCEP-GFS³-Wave and Copernicus Marine GLO-MFC products): the South African Weather
109 Service uses the NCEP-GFS, as well as currents from the Copernicus Marine Service forecasts to run an operational
110 regional and coastal wave and storm surge model (Barnes & Rautenbach, 2020). Additionally, they disseminate
111 regional information based on Copernicus Marine forecasts.
- 112 • South Africa (using Copernicus Marine GLO-MFC products) added regional value to Copernicus Marine products:
113 e.g., marine heat waves, location of the Agulhas Current (e.g. distance from shore), and SST anomalies in an
114 operational service. The tools are currently being integrated into the web portal.

115 **3 West Pacific and Marginal Seas of South and East Asia**

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

²<https://moi.govmu.org/gmes/forecast>

³<https://www.nco.ncep.noaa.gov/pmb/products/gfs/>

119 3.1 Regional and Coastal Forecasts

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

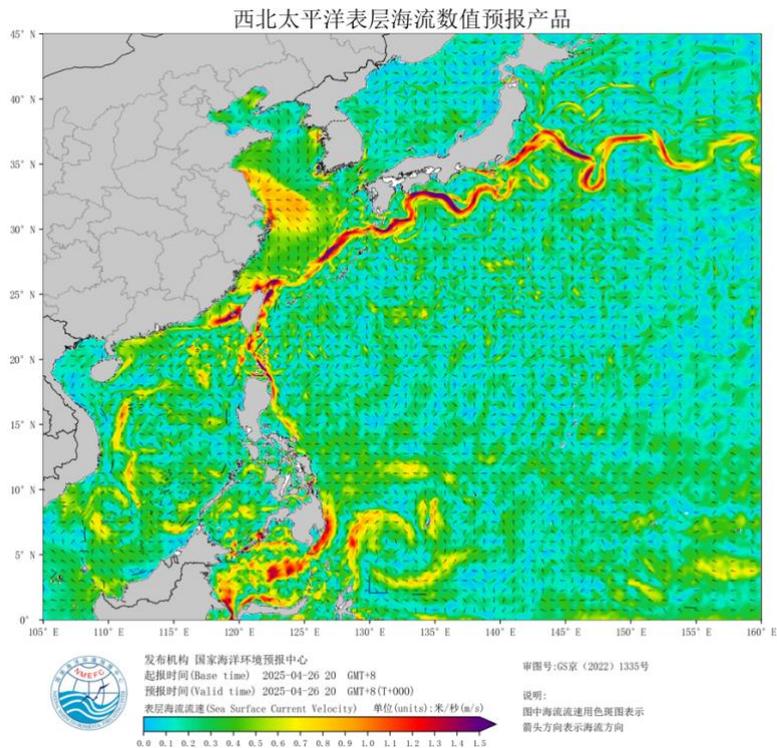
122 The Japan Coastal Ocean Predictability Experiments (JCOPE⁴) system, developed by the Japan Agency for Marine-Earth
123 Sciences and Technology (JAMSTEC) based on the Princeton Ocean Model, is a dynamic ocean monitoring and forecasting
124 system (Miyazawa et al., 2009, 2021). Originally tailored for the western North Pacific at eddy-resolving resolutions, JCOPE
125 is now extended to cover the global ocean with a new eddy-resolving quasi-global ocean reanalysis product, the JCOPE
126 Forecasting Global Ocean (JCOPE-FGO). The model covers the global ocean from 75°S to 75°N except for the Arctic Ocean,
127 with a horizontal resolution of $0.1^\circ \times 0.1^\circ$ and 44 sigma levels. The validation against observational data demonstrates JCOPE-
128 FGO's effectiveness, while assessments using satellite data show its capability in representing upper ocean circulation (Kido
129 et al., 2022). The significance of river forcing for accurately representing seasonal variability is emphasized by highlighting
130 the inclusion of updated global river runoff in JCOPE-FGO and its significant impacts on near-surface salinity.

131 Kyusyu University in Japan operates several real-time ocean forecasting systems based on the Research Institute for Applied
132 Mechanics Ocean Model (DREAMS⁵) system. This 3-dimensional ocean model is formulated in spherical coordinates with a
133 horizontal resolution of approximately 1.5 km and features 114 vertical levels (Liu and Hirose, 2022). Its domain covers a
134 rectangular region southwest of Japan, including part of the East China Sea shelf and the deep Okinawa Trough.

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

⁴https://www.jamstec.go.jp/jcope/htdocs/e/jcope_consortium.html

⁵https://dreams-c1.riam.kyushu-u.ac.jp/vwp/html/vwp_about.html.ja



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

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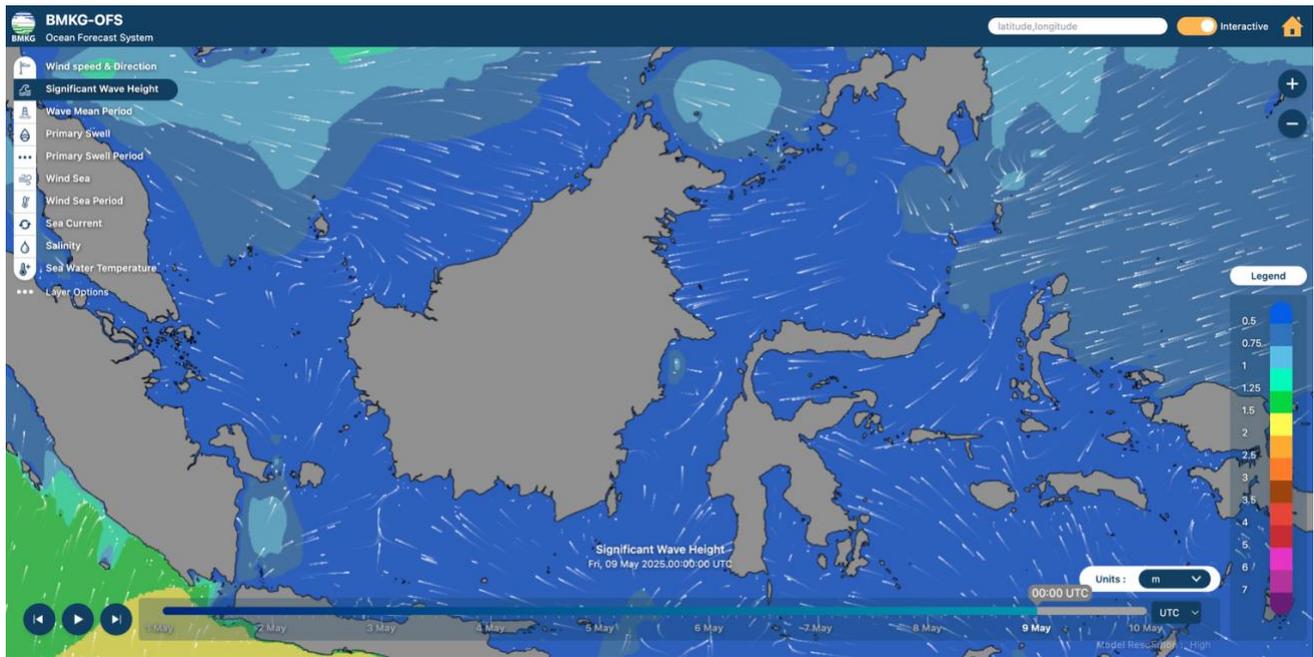
The BMKG Ocean Forecast System (BMKG-OFS⁶) is an advanced forecasting system developed by Indonesia's Meteorological, Climatological, and Geophysical Agency (BMKG) to provide accurate and timely oceanographic information for the Indonesian seas (Figure 3). Launched in 2017, BMKG-OFS offers up to seven-day 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.

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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.

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⁶<https://maritim.bmkg.go.id/ofb>



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

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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 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.

Bluelink⁷ 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 (OceanMAPS⁸), provides seven-day forecasts of ocean conditions, including

⁷<https://research.csiro.au/bluelink/global/forecast/>

⁸<http://www.bom.gov.au/marine/index.shtml>

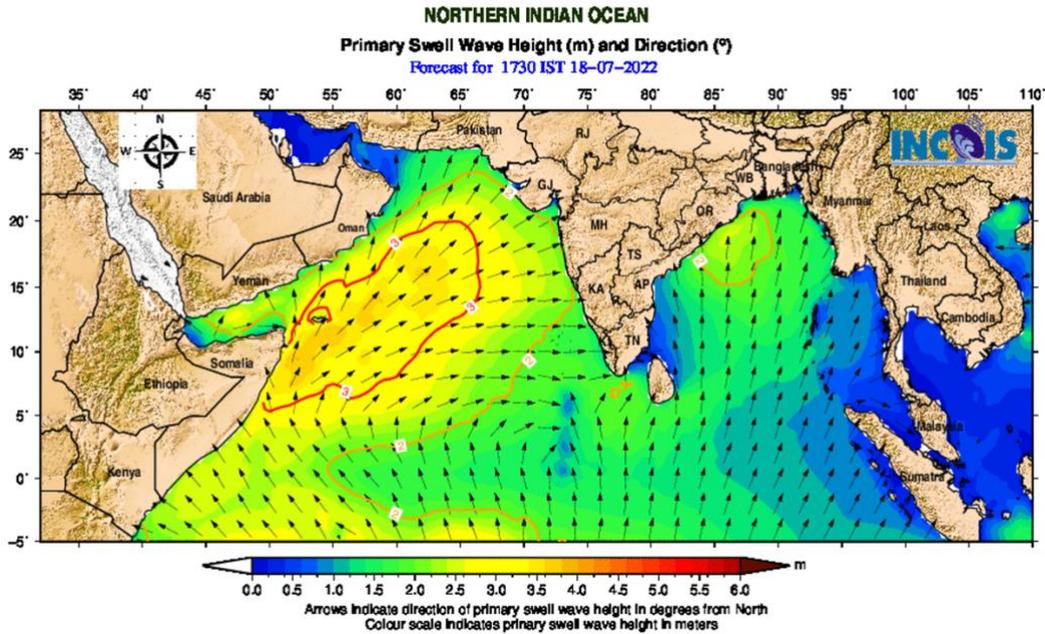
182 currents, temperature, salinity, and sea level, on a near-global scale. These forecasts are crucial for various sectors, including
183 maritime industries, defence applications, and climate research, aiding in decision-making and enhancing safety at sea
184 (Brassington et al., 2023). The version 4 operational since 2022 uses the ensemble Kalman filter (EnKF).

185 **4 Indian Ocean**

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

196 **4.1 Regional systems**

197 The Indian National Centre for Ocean Information Services (INCOIS) operates two regional ocean forecasting systems
198 utilizing the Hybrid Coordinate Ocean Model (HYCOM) and the Regional Ocean Modelling System (ROMS). The regional
199 INCOIS-HYCOM has the highest resolution of approximately 6.9 km, followed by regional INCOIS-ROMS with
200 approximately 9.2 km resolution. Regional INCOIS-HYCOM is forced with atmospheric variables from the NCEP-GFS and
201 uses and assimilates Sea Surface Temperature (SST) data derived from the Advanced Very High-Resolution Radiometer
202 (AVHRR) sensor, along track sea-level anomalies, in-situ profiles from various observing platforms using Tentral Statistical
203 Interpolation Scheme (TSIS) Data Assimilation (DA) method (Srinivasan et al., 2022), taking boundary conditions from
204 INCOIS GLOBAL HYCOM described earlier (Table 1).



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

207 Regional ROMS model from INCOIS uses atmospheric forcing from the National Centre for Medium Range Weather
 208 Forecasting (NCMRWF⁹) Unified Model (NCUM) atmospheric system. It assimilates SST and vertical profiles of temperature
 209 and salinity from in-situ platforms using Local Ensemble Kalman Filter (LETKF) DA method. Data visualization and products
 210 from these models are available through web interface (<https://incois.gov.in/portal/osf/osf.jsp>) to users and data is made
 211 available to users on request.

212 INCOIS also provides operational wave forecasts through its integrated Indian Ocean Forecasting System (INDOFOS¹⁰).
 213 These forecasts are essential for maritime safety, navigation, and various ocean-based activities. INCOIS utilizes the third-
 214 generation wind-wave model WAVEWATCH III (Tolman, 2009) (Figure 4).

215 **4.2 Coastal systems**

216 INCOIS ROMS-Coastal is the only coastal model identified for the Indian Seas. It has approximately 2.3 km spatial resolution
 217 which is forced with the same NCUM atmospheric variables as in case of regional ROMS and does not assimilate any data but
 218 takes initial and boundary conditions from regional 9.2 km ROMS. Data visualization and products are made available through
 219 dedicated INCOIS web portal¹¹ and data is available to users on request.

⁹<https://www.ncmrwf.gov.in/>

¹⁰https://incois.gov.in/portal/osf/osf_rimes/index.jsp

¹¹<https://incois.gov.in/portal/osf/osf.jsp>

220 **5 African Seas**

221 The African Seas can be subdivided into six regions, based on distinct ecosystem characteristics: the Canary Current Large
222 Marine Ecosystem (LME), the Guinea Current LME, the Benguela Current LME, the Agulhas-Somali Current LME, the Red
223 Sea LME and the Mediterranean Sea LME. Aside from the Mediterranean Sea LME, that will be discussed separately, an
224 overview of the landscape with respect to operational ocean forecast services will be provided below. Operational ocean
225 modelling is a developing field, with limited capacity in most parts of Africa. Operational services in these regions therefore
226 depend largely on core global products and vary in levels of complexity, from disseminating locally relevant information via
227 monthly bulletins to limited area forecast models that use global products at their boundaries. While various types of ocean
228 forecast services exist to support national priorities, two consortia have been developed through Global Monitoring for
229 Environment and Security (GMES¹²) and Africa to provide more regional support for marine and coastal operations. These
230 are Marine and Coastal Operations for Southern Africa and the Indian Ocean (MarCOSIO¹³) and Marine and Coastal Areas
231 Management in North and West Africa (MarCNoWA¹⁴). These platforms currently make use of global services for Earth
232 Observations (EO) as well as marine forecast products that in some cases are optimized for local conditions.

233 **5.1 Regional systems**

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

- 235 ● The Iberia-Biscay-Ireland Marine Forecasting Centre (IBI-MFC¹⁵) Ocean Physics, Waves and Biogeochemistry
236 Analysis and Forecast products, provided by the Copernicus Marine Service, are suitable for use by regional services
237 in North and Northwest Africa.
- 238 ● Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES¹⁶) has developed an integrated
239 high resolution regional ocean forecasting system that encompasses the ocean regions of Madagascar, Mozambique
240 and Seychelles.
- 241 ● The Integrated Red Sea Model (iREDS-M1) has been developed by the King Abdullah University of Science and
242 Technology in Saudi Arabia. Its atmospheric and ocean (wave and general circulation) models are running on an
243 operational basis to provide short-range forecasts for the Red Sea (Hoteit et al., 2021).
- 244 ● The South African Weather Service (SAWS¹⁷) provide regional wave, wave-current interaction and tide forecasts,
245 downscaled from global services, none of which are assimilative (Barnes and Rautenbach, 2020). They also provide
246 an empirically derived algorithm-based forecast of the sea-ice edge for METAREA VII (De Vos et al., 2021).

¹²<https://gmes.rmc.africa/>

¹³<https://marcosio.org/>

¹⁴<https://geoportal.gmes.ug.edu.gh/#/>

¹⁵<https://marine.copernicus.eu/about/producers/ibi-mfc>

¹⁶<https://rimes.int/>

¹⁷<https://www.weathersa.co.za/>

- 247 ● The MarCNoWA focuses on delivering Earth Observation (EO) services on coastal and marine environments and
248 fisheries:
- 249 ○ Provision of potential fishing zone charts overlaid with vessel traffic,
 - 250 ○ Monitoring and forecasting oceanography variables,
 - 251 ○ Forecast of ocean conditions,
 - 252 ○ Oil spill monitoring,
 - 253 ○ Generation of coastal vulnerability indices, and Mapping of coastal habitats.

254 Through a network of national stakeholders, regional fisheries and environmental bodies, academia, private sector
255 and researchers, the project is to impact decision making in the beneficiary countries. It downscales Copernicus
256 Marine products and provides forecasts (Forecasts - Global Monitoring for Environment and Security & Africa
257 (rnc.africa).

- 258 ● The forecasting system GCOAST¹⁸, developed by HEREON, is implemented at regional scale for the western coast
259 of Africa. The GCOAST¹⁹ (Geesthacht Coupled cOAstal model SysTem) is built upon a flexible and comprehensive
260 coupled model system integrating the most important key components of the regional and coastal systems and,
261 additionally, allowing including information from observations. The operational modelling system is developed
262 based on a downscaling approach from the Copernicus Marine GLO-MFC forecast products at 1/12° resolution,
263 focusing on the western African coast. The wind-wave model is based in WAM. The atmospheric forcing is taken
264 from ECMWF.

265 5.2 Coastal systems

266 Operational ocean forecast services for African coasts include:

- 267 ● The National Coastal Forecasting System for Mozambique (FEWS-INAM) provides 3-day ocean and meteorological
268 forecasts in the form of daily bulletins and text messages to support operations at sea. It uses global NCEP-GFS data
269 to provide meteorological and wave boundaries, and GLOSSIS²⁰ for the storm surge boundary conditions. The
270 forecasts include wave information, tide and surge water levels and atmospheric weather information. This system
271 was developed by a consortium, including Mozambique's Met Office INAM31, Deltares, UK Meteorological Office
272 and the DNGRH.
- 273 ● SAWS provides higher resolution wave forecasts, optimized for key coastal regions as well as storm surge forecasts.
274 The information is disseminated on their web portal https://marine.weathersa.co.za/Forecasts_Home.html

¹⁸https://www.hereon.de/institutes/coastal_systems_analysis_modeling/research/gcoast/

¹⁹https://www.hereon.de/institutes/coastal_systems_analysis_modeling/research/gcoast/index.php.en

²⁰<https://www.deltares.nl/en/expertise/projects/global-storm-surge-information-system-glossis>

- The SOMISANA²¹ (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:

 - Algoa Bay and the
 - Southwest Cape Coast.

The models run daily and provide 5-day forecasts of currents, temperature and salinity through the water column (Figure 5). 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/>. 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 municipality²². 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.

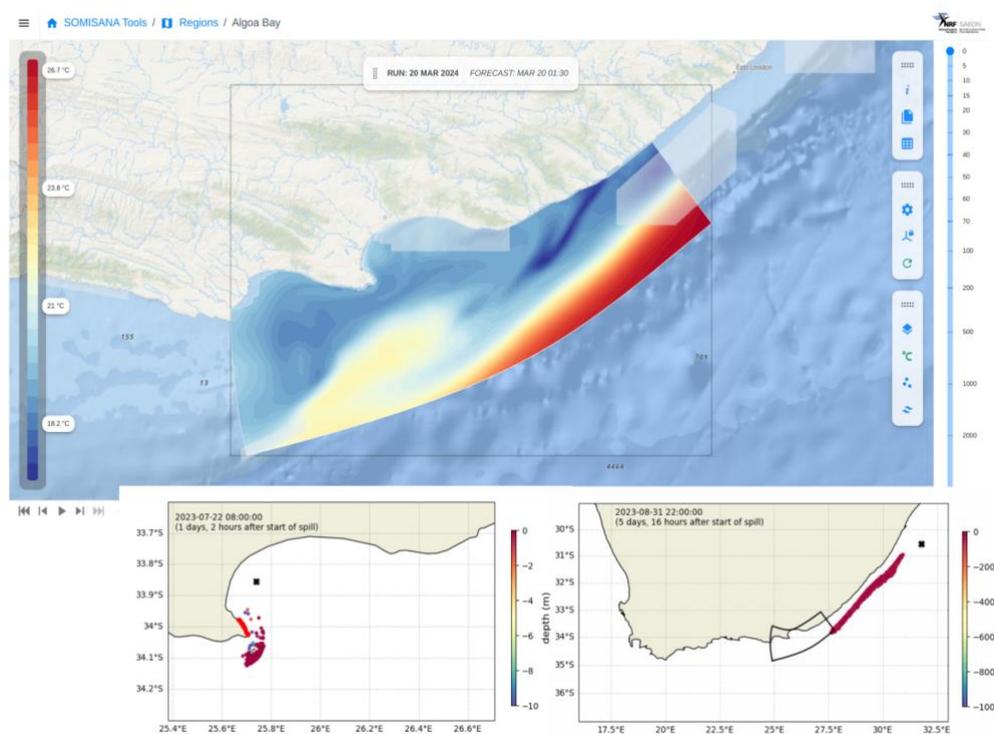


Figure 5. The web-portal of the bay-scale forecast system developed by the SOMISANA team in South Africa. The web portal allows users to explore the variables as well as to scrutinize various depth-levels of the forecasts. The insets show the oil-spill tracking functionality, developed using the OpenDrift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

²¹<https://somisana.ac.za/>

²²<https://publications.deltares.nl/EP4040.pdf>

291 The coastal forecasting system developed in response to extreme storm surge, waves and flooding events along the eastern
292 coast of Ghana utilizes advanced modelling techniques and global forecast services. The coastal model employed in this system
293 is a flexible and modular modelling platform GCOAST (Geesthacht Coupled cOAstal model SysTem) for regional and coastal
294 applications. The hydrodynamical model is based on SCHISM (Semi-implicit Cross-scale Hydrosience Integrated System
295 Model)²³, which is coupled with the wind wave model WWM. The coastal forecasting modelling platform ensures a flexible
296 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
297 provide both hindcasts and forecasts. For hindcast simulations, it uses the GLORYS12 reanalysis (Global Ocean Physics
298 Reanalysis, product ID: GLOBAL_REANALYSIS_PHY_001_030). For forecasts, it uses the GLO-MFC (product ID:
299 GLOBAL_ANALYSIS_FORECAST_PHY_001_024). Atmospheric forcing is provided by the ECMWF operational forecast
300 products. At the boundaries, the model is coupled to the Global Ocean Physics Reanalysis GLORYS²⁴ provided by the
301 Copernicus Marine Service (as part of the GLO-MFC product catalogue) and produced by Mercator Ocean International. The
302 coastal forecasting system incorporates tidal forcing from the Finite Element Solution 2014 (FES2014, Lyard et al., 2021)
303 global ocean tide model, which provides tidal elevations and currents on a 1/16° grid and has demonstrated significant
304 improvements over previous versions, particularly in coastal and shelf regions. This comprehensive approach ensures that
305 stakeholders receive timely and accurate information to prepare and respond effectively to extreme events along the eastern
306 coast of Ghana. In addition to its predictive capability, the system also supports environmental resilience. It integrates
307 mangrove vegetation into the modelling platform to assess and promote nature-based solutions for coastal protection. This
308 component enables the evaluation of scenarios in which mangrove cover is varied to estimate its potential to mitigate wave
309 energy and reduce coastal erosion. The implementation builds on the findings of recent studies demonstrating the buffering
310 role of mangroves against hydrodynamic forces in the coast of Ghana, contributing to sustainable coastal management
311 strategies. These insights guide the design of adaptive coastal management strategies based on nature-based interventions
312 (Jayson-Quashigah et al., 2025).

313 **6 Mediterranean and Black Sea**

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

- 316 • A general concept of operational oceanography was emerging worldwide.
- 317 • The advent of new ocean monitoring technologies allowing for multiplatform systems, including both in-situ
318 monitoring and satellite remote sensing, that in addition to the development of internet network connections started
319 providing open data with a near-real time availability (Tintorè et al., 2019).

²³<https://ccrm.vims.edu/schismweb/>

²⁴https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description

- 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 ARENA²⁵ 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 (MonGOOS²⁶). Also, the Black Sea Community, within the Global Ocean Observing System, has been established into the Black Sea GOOS²⁷.

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

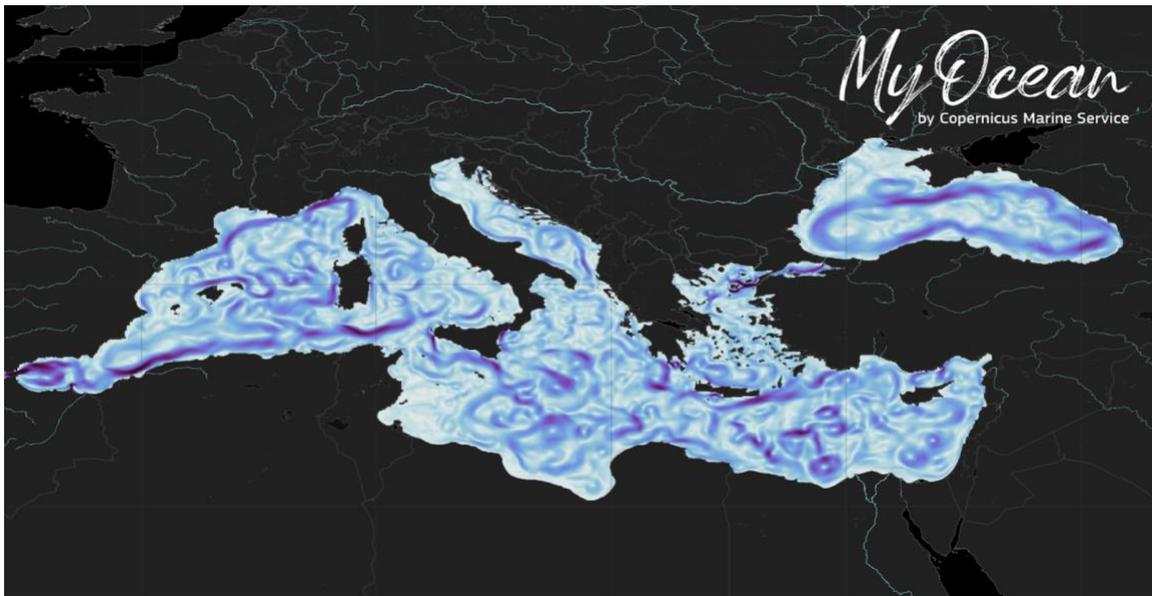
There are a limited number of regional forecast systems optimized specifically for African Seas.

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).

²⁵http://old.ims.metu.edu.tr/black_sea_goos/projects/arena.htm

²⁶<https://mongoos.eurogoos.eu/>

²⁷<https://eurogoos.eu/black-sea/>



340

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

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

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

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

- 358 • A high-resolution Mediterranean and Black Sea system based on MITGCM (Massachusetts Institute of Technology
 359 General Circulation Model, Marshall et al., 1997) described in Palma et al. (2020). The system includes tides, is
 360 resolved at a 2 km resolution (and higher resolution in specific areas) and is nested in the Med-MFC. This system has

361 been used as a basis to develop a 1/16° model to assess present and future climate in the Mediterranean Sea focusing
362 on sea-level change - MED16 (Sannino et al., 2022).

- 363 ● The KASSANDRA²⁸ storm surge forecasting system for the Mediterranean and Black Seas which is based on the
364 coupled hydrodynamic SHYFEM (Umgiesser et al., 2004) and wave (WaveWatchIII) models allowing for very high
365 resolution in specific areas (Ferrarin et al., 2013).
- 366 ● The MFS²⁹ developed at INGV (National Institute of Geophysics and Volcanology, Italy) with 1/16° resolution, based
367 on NEMO and implementing a 3D variational data assimilation scheme (OceanVar, Dobricic and Pinardi, 2008).
- 368 ● The physical and wave ocean system MITO (Napolitano et al., 2022) provides 5 days forecasts of the Mediterranean
369 Sea circulation based on the MITGCM, is forced by the Copernicus Mediterranean physical and wave forecasting
370 products to generate 5-day forecasts data at a horizontal resolution up to 1/48° degree.
- 371 ● The POSEIDON³⁰ basin-scale Mediterranean forecasting system (~10 km resolution) ocean and ecosystem state,
372 developed at HCMR (Hellenic Centre for Marine Research, Greece). This includes a hydrodynamic model, based on
373 POM (Princeton Ocean Model, Blumberg and Mellor, 1987), which assimilates satellite and in situ data (Korres et
374 al., 2007) and a biogeochemical model, based on ERSEM (European Regional Seas Ecosystem Model, Barretta et
375 al., 1995; Kalaroni et al., 2020a, 2020b).
- 376 ● The CYCOFOS wave forecasting system provides a 5 days forecast of the Mediterranean and the Black Sea (Zodiatis
377 et al. 2018a) based on the WAM model and is forced by the SKIRON high frequency winds.

378 **6.2 Coastal systems**

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

384 **HYDRODYNAMICS:**

- 385 ● The IBI-MFC Physics Analysis and Forecasting System³¹ provides operational analysis and forecasting data at 1/36°
386 resolution implementing the NEMO model integrated with a data assimilation scheme SAM2, which allows a
387 multivariate assimilation of sea surface temperature together with all available satellite sea level anomalies and in situ
388 observations.

²⁸<http://kassandra.ve.ismar.cnr.it:8080/kassandra>

²⁹<https://medforecast.bo.ingv.it/>

³⁰www.poseidon.hcmr.gr

³¹<https://doi.org/10.48670/moi-00027>

- 389 ● The “Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria”, SAMOA (Álvarez Fanjul et al.,
390 2018; Sotillo et al., 2019; Garcia-Leon et al., 2022), provides operational downstream services and a significant
391 number of high-resolution forecasting applications, based on Copernicus Marine forecasting services and Spanish
392 Meteorological Agency (for atmospheric forecast), including 20 atmospheric models, 21 wave models and 31
393 circulation models. implements the ROMS (Regional Ocean Modeling System) model at a resolution of 350 to 70 m.
- 394 ● The WMOP model (Juza et al., 2016; Mourre et al., 2018) based on ROMS is a downscaling of the Copernicus
395 Mediterranean system with a spatial resolution of 2 km and covering the Western Mediterranean basin from the Strait
396 of Gibraltar to the longitude of the Sardinia Channel. It is implemented by SOCIB (Balearic Islands Coastal Observing
397 and Forecasting System) and is run operationally on a daily basis, producing 72-hour forecasts of ocean temperature,
398 salinity, sea level and currents.
- 399 ● A high-resolution numerical model, developed as part of an operational oceanography system in the frame of the
400 “Sistema Autonomo de Medicion, Prediccion y Alerta en la Bahia de Algeciras” (SAMPA) project is implemented
401 by Puertos Del Estado (Spain) providing operational ocean forecast data in the complex dynamical areas of the
402 Gibraltar Strait and the Alboran Sea.
- 403 ● The MARC (Modelling and Analyses for Coastal Research) and ILICO (Coastal Ocean and Nearshore Observation
404 Research Infrastructure) are implemented using MARS3 model in the Bay of Biscay/English Channel/Northwestern
405 Mediterranean Sea at 2.5 km horizontal resolution and nested in the Copernicus Global system.
- 406 ● The Tyrrhenian and Sicily Channel Regional Model, TSCRM (Di Maio et al., 2016; Sorgente et al., 2016), is based
407 on a regional implementation of POM at 2 km resolution and is nested into the Copernicus Mediterranean Analysis
408 and Forecasting system.
- 409 ● The Southern Adriatic Northern Ionian coastal Forecasting System, SANIFS (Federico et al., 2017), is a coastal-ocean
410 operational system based on the unstructured-grid finite-element 3D hydrodynamic SHYFEM model reaching a
411 resolution of a few meters. It is a downscale of the Med-MFC physical product and provides short term forecast fields.
- 412 ● The Aegean and Levantine Eddy Resolving Model, ALERMO (Korres and Lascaratos, 2003), is based on POM
413 implemented at 1/48° resolution and nested into the Copernicus Mediterranean Analysis and Forecasting system.
- 414 ● The Cyprus Coastal Ocean Forecasting and Observing System, CYCOFOS (Zodiatis et al., 2003, 2018b) is
415 specifically developed to provide a sub-regional forecasting and observing system in the Eastern Mediterranean
416 (including the Levantine Basin and the Aegean Sea). The latest system is forced by the Copernicus Med-MFC
417 Physical forecasting system, implements POM at 2 km resolution to produce initial and open boundary conditions in
418 specific locations.
- 419 ● The TIRESIAS Adriatic forecasting system based on the unstructured grid 3D hydrodynamic model SHYFEM and
420 representing the whole Adriatic Sea together with the lagoons of Marano-Grado, Venice and Po Delta (Ferrarin et al.,
421 2019). It is a downscale of the Med-MFC physical product and provides 3-day forecast fields.

422 WAVES:

- 423 ● The IBI-MFC Waves Analysis and Forecasting system (Toledano et al., 2022) is based on MF-WAM (Meteo-France
424 WAM) implemented at 1/36° resolution and produces waves forecast in the Western part of the Mediterranean Sea
425 twice a day.
- 426 ● The SAPO³² (Autonomous Wave Forecast System) based on WAM model is implemented at several Spanish Ports
427 (Spain) with a horizon of 72 h forecast and it is nested within the PORTUS forecast system, an operational wave
428 forecast for Spanish Port Authorities.
- 429 ● WAMADR setup of ECMWF WAM is implemented by the Slovenian Environment Agency for Adriatic and Central
430 Mediterranean domain with a horizon 72 hours and spatial resolution of 1.6 km. The model is forced by a hybrid
431 ALADIN SI and ECMWF surface wind product and is running daily.
- 432 ● Several coastal and local wave applications providing wave information near the harbours, as well as boundary
433 conditions for specific wave agitation inside the port applications, are using the SWAN model (Booij et al., 1999).

434 BIOGEOCHEMISTRY:

- 435 ● The IBI-MFC Biogeochemical Analysis and Forecasting System³³ is implemented using the PISCES (Aumont et al.,
436 2015) model at 1/36° horizontal resolution.
- 437 ● The Northern Adriatic Reanalysis and Forecasting system (NARF) and the CADEAU physical-biogeochemical
438 reanalysis (Bruschi et al., 2021) are implementing the MITgcm-BFM coupled models in the Northern Adriatic Sea
439 reaching up to 750 m with a further high-resolution (~125 m) nesting in the Gulf of Trieste (<https://medeaf.ogs.it/got>).

440 7 North-East Atlantic

441 Operational oceanography in European countries was mainly operated at a national level until the 1990s. In 1994, the European
442 part of the Global Ocean Observing System (EuroGOOS³⁴) was founded. It grouped these national endeavours into a network
443 of European monitoring and forecasting systems and initiated several regional and thematic working groups to support specific
444 developments. Since the early 1990s, the European Commission has been actively funding programmes to support ocean
445 monitoring and forecasting through, for instance, its series of MyOcean projects (2009–2015) and its ongoing ambitious
446 Copernicus Earth observation programme, which includes the Copernicus Marine Service component.

447 Due notably to the coordinating efforts provided by the Copernicus Marine Service over the last decade, the North-East Atlantic
448 region is now well equipped in terms of operational marine forecasting services. Also, each segment of the North-East Atlantic
449 coastline is included in at least one regional system, such that Global Forecast Services are seldomly used directly, except for
450 the provision of boundary conditions to downstream forecast systems. An inventory of operational marine and coastal models
451 around Europe was compiled out of a survey conducted in 2018–2019 among members of EuroGOOS and its related network

³²https://static.puertos.es/pred_simplificada/Sapo/d.corunia/sapoeng.html

³³<https://doi.org/10.48670/moi-00026>

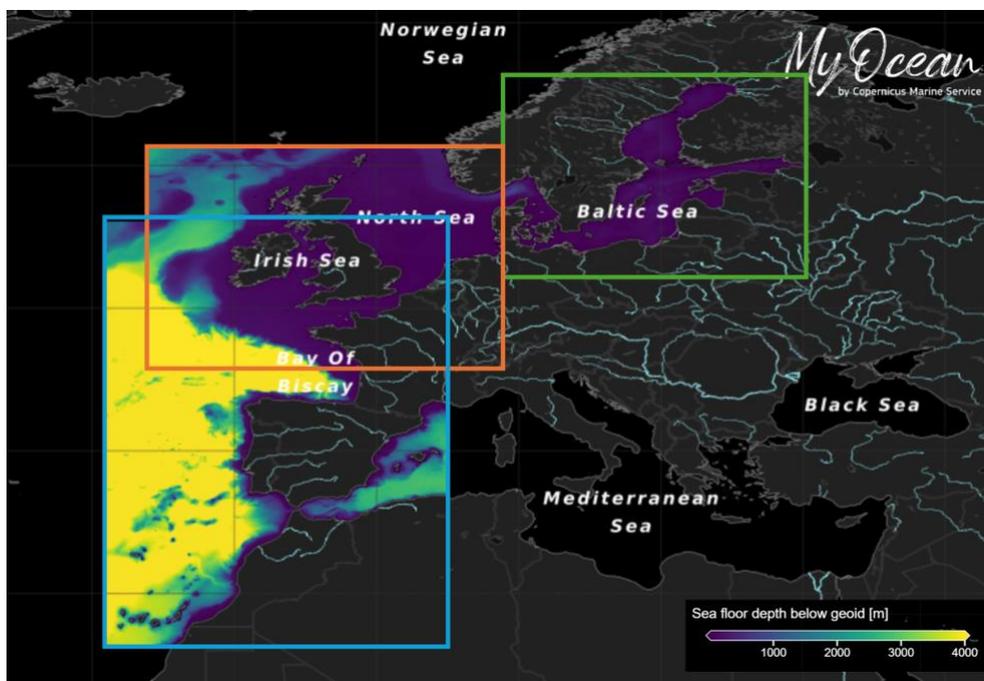
³⁴<https://eurogoos.eu/>

452 of Regional Operational Oceanographic Systems (Capet et al., 2020), addressing the purposes, context, and technical
453 specificities of operational ocean forecasts systems (Oofs). Here, we re-focus this analysis for the North-East Atlantic by
454 excluding the Arctic, Mediterranean, and Black Sea basins from the original analysis. It should be noted that this inventory
455 only includes Oofs actively reported to the survey and might therefore be incomplete. A further expansion of the North-East
456 Atlantic Oofs inventory is expected from the OceanPrediction DCC Atlas.

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

460 7.1 Regional systems in the framework of the Copernicus Marine Service

461 The major marine core service for the North-East Atlantic is provided by the Copernicus Marine Service, and its three regional
462 Monitoring Forecasting Centres (MFCs) dedicated to the Iberian-Biscay-Irish seas (IBI-MFC), European Northwestern
463 Shelves (NWS-MFC³⁵), and Baltic Sea (BAL-MFC³⁶), respectively (Figure 7).



464
465 **Figure 7. The Copernicus Marine regional monitoring and forecasting centers operating in the area: IBI-MFC (in blue), NWS-MFC**
466 **(in orange) and BAL-MFC (in green). The map shows bathymetry (m) and the composite regions obtained from the MyOcean**
467 **Viewer (<https://data.marine.copernicus.eu/viewer>).**

³⁵<https://marine.copernicus.eu/about/producers/nws-mfc>

³⁶<https://marine.copernicus.eu/about/producers/bal-mfc>

468

469 In terms of modelling, each of these three MFCs is composed of dedicated components addressing ocean circulation (PHY),
470 biogeochemistry (BGC), and wave dynamics (WAV). These systems operate under the coordinated umbrella of Copernicus
471 Marine Service and therefore benefit from homogenized protocols in terms of operational data production, validation,
472 documentation, and distribution (Le Traon, 2019). Products and related documentation can be accessed through the central
473 Copernicus Marine Data Store, together with observational datasets including in-situ, remote sensing, and composite products
474 for the Blue (physics and hydrodynamics), Green (biochemistry and biology), and White (sea-ice) ocean. Operational data
475 delivery is provided through online data selection tools and a variety of automatic protocols (e.g., Subset, FTP, WMTS), which
476 effectively enables a number of operational downstream services to depend directly on those core services. A catalogue of
477 such downstream usage and its potentialities is exposed on the Copernicus Marine Use-Cases portal³⁷.

478 **7.2 Other regional systems**

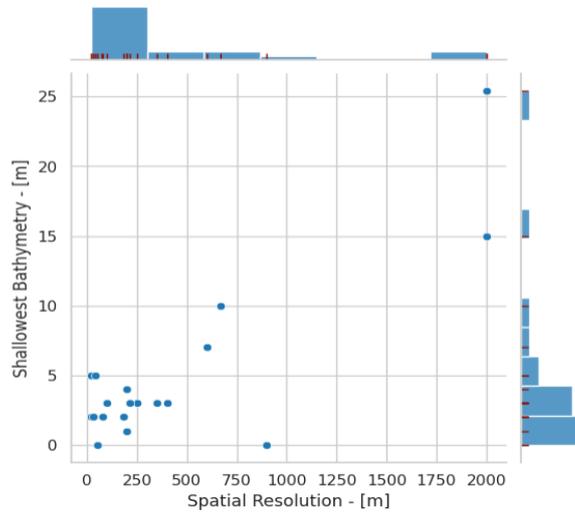
479 The 35 regional forecasts systems that are not operated by Copernicus Marine are mostly operated by national entities and
480 provide data free of charge to relevant users in 71% of the cases. They address circulation (80% of the regional OOFs), wave
481 dynamics (23%) and biogeochemistry (14%),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

487 **7.3 Coastal systems**

488 32 coastal OOFs are reported in the EuroGOOS Coastal Working Group (CWG) inventory for the North Sea, Baltic Sea, and
489 European shelves, addressing circulation (68% of the coastal OOFs), biogeochemistry (29%), and wave dynamics (4%).
490 Again, these OOFs are mostly operated by public entities (although this is recognized as a potential bias in the survey, as
491 discussed in Capet et al. 2020) and provide, in the vast majority, forecast data freely accessible to relevant users.
492 Among coastal OOFs, the usage of land and atmospheric forcing data from specific national sources is much more common
493 than for regional systems, indicating that adequate products are available at local scales. Besides, several coastal system
494 operators rely on their own atmospheric or hydrology model to obtain adequate boundary conditions. One could highlight that
495 15 of the 35 reporting coastal OOFs provide forecasts at a spatial resolution below 500 m, at least in some parts of their
496 domain. In general, such systems also consider fine bathymetry, with a minimal water depth of under 5m (Figure 8).

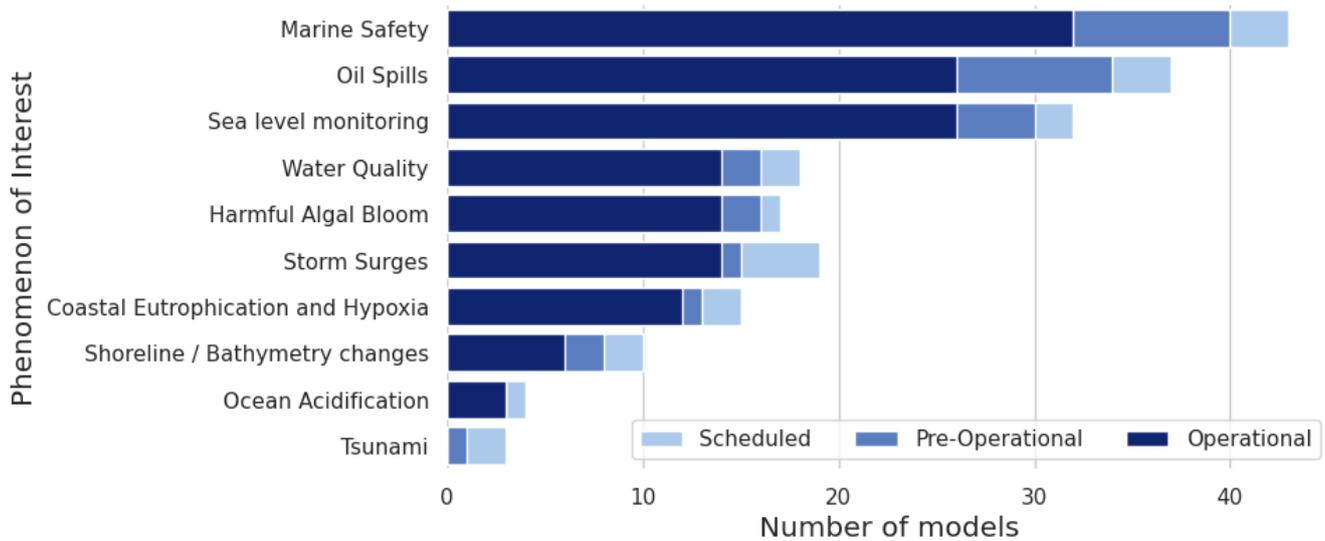
³⁷<https://marine.copernicus.eu/services/use-cases>

497 According to the survey, which was in almost all cases answered by model operators, OOFs in the North-East Atlantic are
 498 relevant for marine safety, oil spills, and sea level monitoring concerns (Figure 9). Yet, the survey did not consider the extent
 499 to which provided information was effectively exploited by downstream operators. To a lesser extent, some systems address
 500 biochemical issues such as water quality, harmful algal blooms, or coastal eutrophication.



501

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



504

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

507 **8 South and Central America**

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

515 **8.1 Regional systems**

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

520 The first operational ocean forecast system with data assimilation in Brazil was implemented in the Brazilian Navy
521 Hydrographic Center (CHM) in 2010 based on the Hybrid Coordinate Ocean Model (HYCOM) and on an optimal interpolation
522 scheme, developed by the Oceanographic Modeling and Observation Network (REMO) (Lima et al., 2013). Since 2014, CHM-
523 HYCOM forecasts was initialized by the REMO Ocean Data Assimilation System (RODAS) (Augusto Souza Tanajura et al.,
524 2014; Tanajura et al., 2020) based on the optimal interpolation scheme, which can assimilate SST analysis, along-track or
525 gridded sea level anomaly (SLA) and T/S vertical profiles. The ensemble members are chosen according to the assimilation
526 day from a previous free run. The most recent CHM-HYCOM+RODAS configuration produces 5-day forecasts daily and
527 encompasses the entire North, Equatorial, and South Atlantic with 1/12° horizontal resolution, to generate boundary conditions
528 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
529 32 vertical hybrid layers. Other models are also employed operationally in CHM. ADCIRC is employed in Guanabara Bay,
530 São Sebastião and Ilha Bela proximities and Sepetiba Bay, as well as in Santos and Paranaguá ports.

531 Regarding the Argentine Sea, the Modelling System for the Argentine Sea (MSAS) is used to model the barotropic component
532 of the ocean state of the Southwestern Atlantic Continental Shelf. MSAS is based on the Coastal and Regional Ocean
533 Community Model (CROCO³⁸). Dinápoli et al. (2023) modified the source code to resolve the depth-averaged horizontal
534 momentum and continuity equations, as well as consider spatially varying bottom friction. MSAS covers the Southwestern
535 Atlantic Continental Shelf with a trapezoidal shape designed to avoid a significant number of land-points and ensure the regular
536 spatial resolution of 8 km in both directions. Along the boundaries, the model is forced with tides and continental discharges,

³⁸<http://www.croco-ocean.org>

537 whereas in the interior of the domain, the ocean surface is forced by atmospheric pressure and surface wind stress (Dinápoli et
538 al. 2020a, 2021, 2023). In addition, MSAS has been used to conduct several scientific studies on the barotropic nonlinear
539 interactions in the region (Dinápoli et al., 2020b), the tidal resonance over the continental shelf (Dinápoli et al., 2024), and the
540 genesis and dynamics of the storm surges along the coast (Alonso et al., 2024). Recently, the Asynchronous Ensemble Square
541 Root Filter (4DEnSRF, Sakov et al., 2010; Whitaker and Hamill, 2002) DA scheme was also incorporated as part of MSAS.
542 The 4DEnSRF scheme is currently used to produce optimal initial conditions for the forecasts by assimilating tidal gauges and
543 remote sensing observations. Because of the large and nonlinear impact of the wind uncertainty on the regional barotropic
544 dynamics (Dinápoli et al., 2020a), an ensemble wind forecast is used. Dinápoli et al. (2023) used the 31-member ensemble
545 from NCEP's Global Ensemble Forecast System, together with a set of perturbations of the tides. Since the atmospheric
546 ensemble provides the wind field, rather than the wind stress, the former is estimated using the parameterization of Simionato
547 et al. (2006). The incorporation of 4DEnSRF into MSAS forecasts, together an ensemble post-processing technique developed
548 by Dinápoli and Simionato (2022), has improved the 96-hr forecasts by reducing the model bias and correcting the timing of
549 the strong storm surges that affect the northern part of the Southwestern Atlantic Continental Shelf. It is important to mention
550 that MSAS is running pre-operatively, and its solutions will be made public soon. Relevant developments have been achieved
551 with regard to wind wave modelling. The numerical model WAVEWATCHIII was regionalized and validated with direct
552 observations from a number of buoys scattered in the Southwestern Atlantic Continental Shelf.

553 In Peru, a large effort in climate modelling has been undertaken in the 2000s to develop sub seasonal forecasts and anticipate
554 the significant socio-economic consequences of the El Niño Southern Oscillation (ENSO). The Geophysical Institute of Peru
555 (IGP) has implemented recently in forecast mode a regional Earth System Model called IGP RESM-COW v1. This system
556 released in December 2023 (Montes et al., 2023) is based on the CROCO ocean model (Debreu et al., 2012) coupled to the
557 WRF atmospheric model through the OASIS coupler (Craig et al., 2017) and now serves as an additional forecasting tool for
558 establishing the recommendations by the ENFEN (Estudio Nacional del Fenómeno El Niño), a governmental body responsible
559 for monitoring, studying, and predicting the El Niño phenomenon and its impacts on the country. The IGP RESM-COW v1
560 has a horizontal resolution of 12km for the ocean component, and 30 km for the atmospheric component. The domain covers
561 the entire Peruvian territory and part of the eastern Pacific. The current implementation takes as input the forecasts of the
562 NOAA CFSv2 global climate model that have been corrected using a combination of Reanalysis data (GLORYS outputs and
563 the NCEP Final Analysis (FNL) data), the climatological averages of the NCEP coupled forecast system model version 2
564 (CFSv2) and of a 22-years long simulation of the IGP RESM-COW v1 model. This allows forecasts of oceanic and atmospheric
565 conditions to be made up to 7 months in advance (Segura et al., 2023). In addition, the Navy of Peru via the Dirección de
566 Hidrografía y Navegación (Dihidronav) had implemented the WAVEWATCH III for representing the wave behaviour at the
567 northern, central and southern off Peru with a prediction up to 5 days³⁹. This product is available for the scientific community
568 and public interested in understanding wave conditions (<https://cpps-int.org/index.php/wave-watch>). Operation systems are

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

569 also under development at IMARPE (Instituto del Mar del Peru, <https://www.gob.pe/imarpe>) based on the CROCO system,
570 which targets the aquaculture industry in Central Peru region (Arellano et al., 2023). IMARPE and IGP also produce forecasts
571 of ocean conditions at regional scale (Equatorial Kelvin wave amplitude in the Eastern equatorial Pacific) at sub seasonal
572 timescales based on shallow water models (Mosquera, 2014; Urbina and Mosquera, 2020).

573 As part as a 10-years long national program (CLAP), CEAZA (Center for Advanced Studies in Aride Zones) is also currently
574 developing an operational forecast system for the Coquimbo region (central Chile) based on CROCO initialized by Mercator
575 forecasts in order to inform the fishery industry and the public. The 7 days lead time forecasts are to be provided through a
576 mobile app (<https://app.ceaza.cl/>) along with real-time observations (temperature, oxygen) from a buoy at Tongoy bay, a hot
577 spot for the scallop aquaculture industry. The system is based on a CROCO configuration at 3 km resolution (Astudillo et al.,
578 2019) and is coupled to a simple biogeochemical model (BioEBUS) that has been tuned and validated for the western coast of
579 South America (Montes et al., 2014; Pizarro-Koth et al., 2019).

580 In Colombia, the Colombia's Marine Meteorological Service (SMM, in Spanish), hosted by the Dirección General Marítima
581 (DIMAR) as part of the Ministry of Defense, has co-developed over the last 8 years the Integrated Forecast System for
582 Comprehensive Maritime Security (SIPSEM, in Spanish; Urbano-Latorre et al., 2023). SIPSEM is an ecosystem of climate
583 services (Goddard et al., 2020) for met-ocean applications, providing a suite of demand-driven and actionable information to
584 ensure maritime safety and protect life at sea, while contributing to international regulations in the SOLAS, SAR, IALA,
585 PIANC, IMO and WMO conventions. Focusing on the ocean component, SIPSEM uses CROCO involving different domains
586 and nests, tailored for the different applications and coastal complexities. Application in regional scale in the Colombian
587 Caribbean and Pacific employs a horizontal resolution equal to 9.16 km. Different CROCO forecasts systems are nested in
588 global forecasts produced by HYCOM+NCODA, Copernicus Global Ocean Physics Analysis and Forecast, and US Global
589 Navy Coastal Ocean Model. They are forced with the Weather and Research Forecast Model (WRF) with 27 km of horizontal
590 resolution nested in GFS forecasts. For wind-generated wave prediction, daily WAVEWATCH III (Tolman et al., 2002)
591 forecasts are used for local and regional areas with 3.7 km and 18.5 km and are periodically calibrated by fine-tuning various
592 model-parameters to best represent the local observations. SWAN (Booij et al., 1999) is also used in nearshore and ports
593 applications. Some key SIPSEM forecasts are publicly available via a web portal⁴⁰ developed targeting the general user.

594 **8.2 Coastal systems**

595 Regional to coastal operational models for the Brazilian Coast started to be developed in 2018 by the Centre for Marine Studies
596 (CEM), from the Federal University of Paraná (UFPR), in collaboration with MARETEC, a research center of the Instituto
597 Superior Técnico (IST – Universidade de Lisboa) from Portugal, through the application of the MOHID modelling system.
598 This initiative, called Brazilian Sea Observatory (BSO), was initially supported by the User Uptake program from Copernicus

⁴⁰<https://meteorologia.dimar.mil.co/>

599 Marine Service. In order to deliver high-resolution forecasts of the Brazilian coast, an operational modelling system was
600 developed based on a downscaling approach from the GLO-MFC physical analysis and forecast system at 1/12° resolution,
601 focusing on the south-eastern Brazilian shelf, including estuarine systems with important port activities and large
602 environmental protection areas. Nowadays, the operational modelling system includes a model covering the south-eastern
603 Brazilian shelf with a horizontal resolution of 1/24°, a model covering the coasts and adjacent shelf of the states of Santa
604 Catarina, Paraná and São Paulo with a horizontal resolution of 1/60°, and high-resolution models (~120 m) for coastal systems
605 (Florianópolis Bays, Babitonga Bay, and Paranaguá Estuarine Complex). The system is maintained by CEM/UFPR.
606 Furthermore, an operational model was developed for the north of Brazil, encompassing the states of Amapá, Pará and
607 Maranhão, and the Amazon River and Pará River estuaries, with a horizontal resolution ranging from 1/24° to 1/60°. The
608 atmospheric forcing comes from the WRF model implemented by the Brazilian National Institute for Space Research (INPE)
609 with 7 km of horizontal resolution. The operational models have a vertical discretization reaching about 1 m of resolution near
610 the surface.

611 In Chile, efforts to implement operational forecasting systems were initially led by the Navy, with a focus on swell forecasting
612 for the entire Chilean coast or some key sites. These efforts have recently diversified to address issues around marine resource
613 management (industrial and artisanal fisheries, aquaculture) and extreme events prediction. They are mostly based on the use
614 of the CROCO system. As part of the national program COPAS Coastal, University of Concepcion is currently developing a
615 forecast coupled systems based on WRF⁴¹, WAVEWATCHIII and CROCO to deliver 3 to 6 days forecasts of oceanic and
616 weather conditions in the harbour of Coronel (378°S). The system is currently delivering operational products at 10 km
617 resolution for the central Chile region (32°-38°S) in uncoupled mode (off-line) . It targets a resolution of 2km in fully coupled
618 mode and extended coverage for the ports of Arica (17.5°S) and Antofagasta (21.5°S). The national Fisheries Development
619 Institute (IFOP) has recently developed an operational system called MOSA for the South part of central Chile focused on the
620 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
621 atmospheric forcing is derived from a forecast run based on WRF at 3 km with open boundary conditions from the Global
622 Forecast System (NCEP-GFS). Ocean boundary conditions are from GLO-MFC physical forecast products and river run-offs
623 from 35 point sources are used based on the FLOW products. Forecasts are provided on-line.

624 Besides these initiatives funded by the academic and public sectors, there are some private companies that also provide ocean
625 and atmospheric forecasting for port operations in Chile. Siprol SpA provides wave, wind, and waves forecasts. They also
626 provide wave forecasting for Ecuador. Also, the company PRDW provides the Automated Wave Forecast System (AWFOS),
627 with 3hrs to 10 days forecasting using a mathematical model coupled with a global wave model wave for deep waters. PRDW
628 also provides forecasting for various sites in South American countries. Finally, the Port of San Antonio, the first port in Chile
629 in terms of port operations, is using models from the Direction of Port Construction (Dirección Obras Portuarias) in
630 collaboration with the National Institute of Hydraulic of Chile (<https://www.dop.pelcam.io/about>). The wind forecasting is

⁴¹<https://www.mmm.ucar.edu/models/wrf>

631 provided by the San Antonio Port Company (EPSA). In all the above, it is unknown the model used, validation and details in
632 model configuration. Coastal applications employ 1.83 km and port applications employ a grid with resolution varying from
633 750 m to 150 m. The daily prediction system also involves an ensemble of CROCO forecasts, continuously calibrated using a
634 pattern-based approach for the regional domain, and an additional local calibration for the coastal domains at higher
635 resolutions.

636 **9 North America**

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

642 **9.1 Regional systems**

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

648 The developments of these foundational systems led to a recognition within the Government of Canada of the potential benefits
649 that could be achieved through the development and implementation of a hierarchy of operational oceanographic systems and
650 products. As a result, the Canadian Operational Network for Coupled Environmental Prediction Systems (CONCEPTS⁴²)
651 initiative was put in place between Environment Canada, the Department of Fisheries and Oceans and the Department of
652 National Defence (Smith et al., 2013b; <https://science.gc.ca/site/science/en/concepts>). The CONCEPTS initiative developed
653 strong ties to Mercator Ocean to accelerate the development of a Canadian ocean assimilation capacity to complement the
654 expertise in ice-ocean modelling and atmosphere-ice data assimilation. This effort produced the Global Ice Ocean Prediction
655 System (GIOPS⁴³; Smith et al., 2016) which paved the way for the first-ever operational global medium-range fully-coupled
656 atmosphere-ice-ocean forecasting system (Smith et al., 2018). Subsequently, a 16-day and monthly ensemble coupled
657 forecasting system was implemented (Peterson et al., 2022) based on the same ice-ocean model configuration and initialized
658 using GIOPS analyses.

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>

659 In 2017, the Canadian Government agreed to take responsibility for METAREA regions 17 & 18 of the Global Marine Distress
660 and Safety System. This required the dissemination of warnings for the weather and ice hazards over a pie-shaped region
661 stretching from the Bering Strait to North of Greenland and up to the north pole. As a result, the Regional Ice Ocean Prediction
662 System (RIOPS⁴⁴; Smith et al., 2018) was developed to produce analyses and forecasts over METAREA 17 & 18 regions, but
663 also including all Canadian coastal waters from 44°N in the Pacific Ocean through the Arctic and down to 26°N in the Atlantic
664 Ocean. RIOPS evolved from an initially ice-only system (Buehner et al., 2016; Lemieux et al., 2016) based on the development
665 of the CREG12 ocean configuration (Dupont et al., 2015).

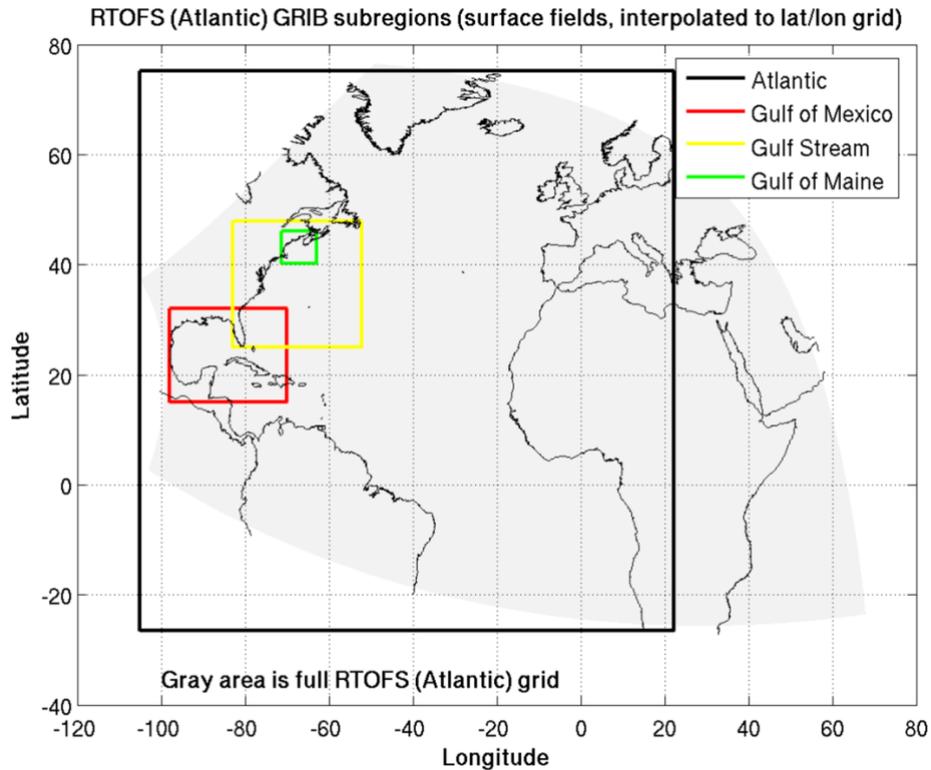
666 As part of the Year of Polar Prediction (YOPP; Goessling et al. 2016) from 2017-2019, a pan-Arctic high-resolution coupled
667 atmosphere-ocean system was developed and run operationally to support Arctic field campaigns and operational activities.
668 This system, called the Canadian Arctic Prediction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

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

675 NOAA operates different ocean forecasting systems to support monitoring in the US region. The (Atlantic) Real-Time Ocean
676 Forecast System (RTOFS⁴⁵) is a regional data-assimilating nowcast-forecast system operated by the NCEP, based on the
677 HYCOM model. The grid is telescopic and orthogonal, varying from approximately 4-5 km near the US East Coast to almost
678 17 km near West Africa (Figure 10) (Mehra and Rivin, 2010). The system runs on a daily basis with a 24 hours assimilation
679 hindcast and produces 2D ocean forecasts on hourly basis for sea surface height (m), sea surface salinity (PSU), sea surface
680 temperature (Celsius), sea surface currents (m/s) and mixed layer thickness (m) and 3D ocean forecasts over 40 pressure levels
681 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>



682

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

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

693 The operational Hurricane Analysis and Forecast System (HAFS⁴⁶) of NCEP provides a reliable and skillful model on Tropical
 694 Cyclone track and intensity since 2023. It is forced by atmospheric fields provided by the NOAA Global Forecast System
 695 (NCEP-GFS) and uses as ocean initial/boundary conditions the RTOFS fields. HAFS is configured with two storm-centric
 696 domains with nominal horizontal resolutions of 6 km and 2 km, respectively.

⁴⁶<https://www.aoml.noaa.gov/hurricane-analysis-and-forecast-system/>

697 NOAA Tide Predictions⁴⁷ system provides tidal forecasts in specific stations located in the West Coast, the East Coast, in the
698 Gulf Coast, in the Pacific and Caribbean Islands. Queries are allowed on hourly, 15- and 6 minutes frequencies
699 The Instituto de Ciencias de la Atmósfera y Cambio Climático at the Universidad Nacional Autónoma de México (UNAM)
700 has developed and currently maintains a regional forecast system that includes meteorology (for Mexico and adjacent regions),
701 ocean circulation (currently the Gulf of Mexico), waves (global and regional with higher resolution), sea level, tides and storm
702 surge, volcanic ash dispersion, oil spill dispersion in the ocean and fire smoke dispersion.
703 The different components of the system began to work in different years, and UNAM has tried to keep them working every
704 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
705 developed for other institutions such as the Mexican National Weather Service, PEMEX (e.g., the national oil company), and
706 CENAPRED, which is part of the national civil system protection. Table 2 summarizes the main characteristics of systems
707 operating in Mexico.
708

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

Component	Model	Domain	Resolution	Start date
Meteorology	WRF-UNAM ⁴⁸	122.5°W to 75.0°W and 0.0°N to 37.0°N	15 km / 5 km	2007
Ocean Circulation	HYCOM-UNAM ⁴⁹	18.0°N to 32.0°N and 98.0°W to 76.0°W	1/25°	2014
Waves	WWIII-UNAM	15.0°N to 38.0°N and 100.0°W to 75.0°W	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: 101.0°W to 96.0°W and 17.0°N to 21.0°N	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/>

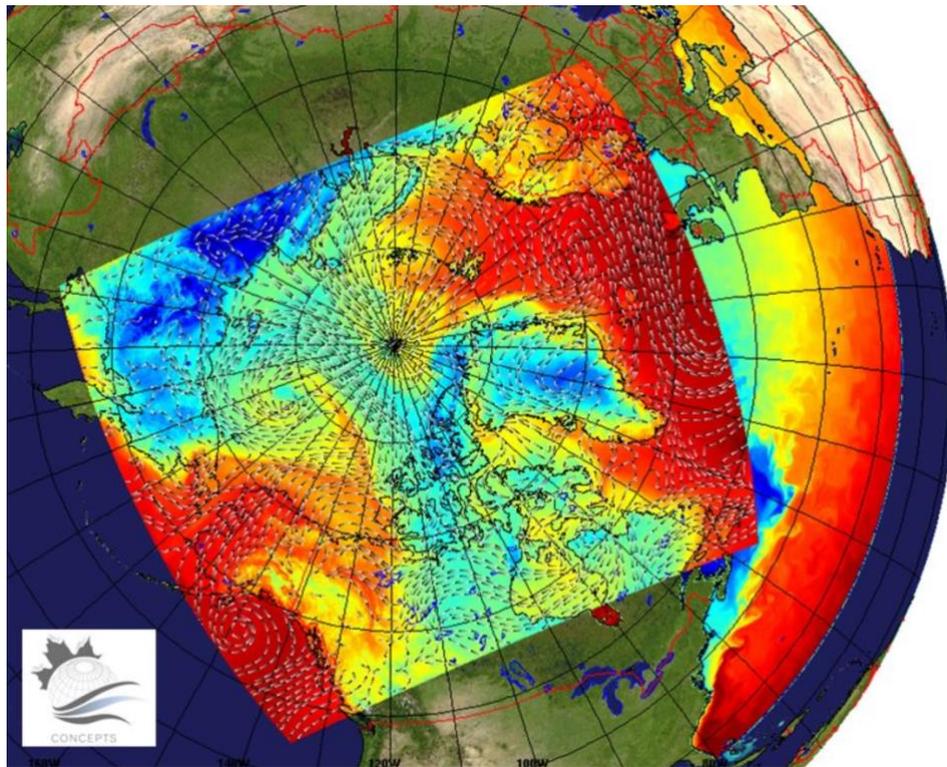
711 Operational ocean circulation model for Gulf of Mexico circulation operates at a resolution of $1/25^\circ$ of a degree using HYCOM,
712 generating hourly output on a daily basis. The model utilizes a distinct bathymetry and coastline compared to the HYCOM
713 Consortium's model. Surface forcings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

724 **9.2 Coastal systems**

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

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

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



739

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

744 The operational CONCEPTS systems products are available through the Meteorological Service of Canada Open Data
 745 platform (Data list /Liste des données - MSC Open Data / Données ouvertes du SMC), including direct data access and
 746 geospatial web services (Figure 11). Data are also available for download and visualization from the Ocean Navigator⁵⁴.

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

748

- In the Pacific:

749

- West Coast Operational Forecast System (WCOFS⁵⁵) 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 24°N (Mexico) to 54°N (British Columbia), with an horizontal resolution that varies from 2 to 4 km. It assimilates SST, sea surface currents (SSUV), SLA using the 4DVAR scheme (Kurapov et al., 2017).

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754

⁵⁴<https://www.oceannavigator.ca/public/>

⁵⁵<https://tidesandcurrents.noaa.gov/ofs/wcofs/wcofs.html>

- 755 ○ Cook Inlet Operational Forecast System (CIOFS⁵⁶) generates water levels, water temperature and salinity,
756 winds nowcast and forecast up to 48 hours, 4 times per day. The system is based on ROMS and uses
757 orthogonal grid with horizontal resolution that spans from 10 m within the estuaries and navigation channels
758 to 3.5 km near offshore waters.
- 759 ○ Salish Sea and Columbia River Operational Forecast System (SSCOFS⁵⁷) provides nowcast and forecast for
760 water levels, currents, water temperature and salinity, incorporating river forcing from available observations
761 and tidal forcing. The model has an unstructured triangular grid. The resolution varies from ~ 100 m along
762 the shoreline to 500 m in deeper parts of Puget Sound and the Georgia Basin, and increases to 10,000 m over
763 the continental shelf. Resolution in the Columbia River varies between 100 and 200 m.
- 764 ○ San Francisco Bay Operational Forecast System (SFBOFS⁵⁸) is based on FVCOM for providing a nowcast
765 and forecast of water levels, temperature and salinity in the San Francisco Bay and in the San Francisco Bay
766 Entrance. The grid has a minimum depth of 0.2 m and maximum depth of 106.8 m. Grid resolution ranges
767 from 3.9 km on the open ocean boundary to approximately 100 m near the coast, indicating the flexibility of
768 the grid size based on bathymetry from the deep ocean to the coast. Additionally, the higher resolution along
769 the navigational channels within the bay, from approximately 100 m to 10 m, provides detailed current
770 features.
- 771 ● In the Great Lakes, 4 FVCOM-based operational systems are available:
- 772 ○ Lake Erie Operational Forecast System (LEOFS⁵⁹) at horizontal resolution from 400 m to 4 km, with higher
773 resolution along the shoreline and in the shallow western basin and coarser resolution for the open waters in
774 the mid and eastern basins.
- 775 ○ Lake Michigan and Huron Operational Forecast System (LMHOFS⁶⁰), at horizontal resolution from 50 m to
776 2.5 km, with higher resolution along the shoreline and in the shallow western basin and coarser resolution
777 for the open waters in both lakes.
- 778 ○ Lake Ontario Operational Forecast System (LHOFS⁶¹), at horizontal resolution from 200 m to 2.5 km, with
779 higher resolution along the shoreline.
- 780 ○ Lake Superior Operational Forecast System (LSOFS⁶²), at horizontal resolution 200 m to 2.5 km, with higher
781 resolution along the shoreline.
- 782 ● In the Gulf of Mexico:

⁵⁶<https://tidesandcurrents.noaa.gov/ofs/ciofs/ciofs.html>

⁵⁷https://tidesandcurrents.noaa.gov/ofs/dev/sscofs/sscofs_info.html

⁵⁸https://tidesandcurrents.noaa.gov/ofs/sfbofs/sfbofs_info.html

⁵⁹https://tidesandcurrents.noaa.gov/ofs/leofs/leofs_info.html

⁶⁰https://tidesandcurrents.noaa.gov/ofs/lmhofofs/lmhofofs_info.html

⁶¹https://tidesandcurrents.noaa.gov/ofs/loofs/loofs_info.html

⁶²https://tidesandcurrents.noaa.gov/ofs/lsofs/lsofs_info.html

- 783 ○ Northern Gulf of Mexico Operational Forecast System (NGOFS⁶³), based on FVCOM with resolution from
784 10 km on the open ocean to approximately 600 m near the coast. Additional refinement of the grid is provided
785 within the bays from 45 m to 300 m. The system runs 4 times per day providing a forecast up to 48 hours.
- 786 ○ Tampa Bay Operational Forecast System (TBOFS⁶⁴), based on ROMS, with a resolution from 100 m to 1.2
787 km. It has been designed to include the whole Tampa Bay and the shelf to properly represent the dynamics
788 at the entrance to the bay.
- 789 ● In the Atlantic, 5 ROMS-based systems provide nowcasts and forecasts up to 48 hours 4 times per day:
- 790 ○ Chesapeake Bay Operational Forecast System (CBOFS⁶⁵), with a resolution spanning from 30 m to 4 km.
791 ○ Delaware Bay Operational Forecast System (DBOFS⁶⁶), with a resolution ranging from 100 m up to 3 km.
792 ○ Gulf of Maine Operational Forecast System (GoMOFS⁶⁷), at 700 m resolution approximately, with forecast
793 horizon up to 72 hours.
794 ○ New York and New Jersey Operational Forecast System (NYOFS⁶⁸), that provides water levels and currents
795 using a grid with horizontal resolution from 5 m to 7.5 km.
796 ○ St. John's River Operational Forecast System (SJROFS⁶⁹), with horizontal resolution from 80 m to 4 km.

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

- 800 ● Coastal Storm Modeling System (CoSMoS), developed by United States Geological Survey (USGS): it is a storm-
801 induced coastal flooding, erosion, and cliff failures system for the North-Central Coast, San Francisco Bay, Southern
802 California and the Central California coast (Barnard et al., 2014).
- 803 ● West Florida Coastal Ocean Model (WFCOM), developed by the USF College of Marine Science in Florida: it is an
804 unstructured grid FVCOM in the Eastern Gulf of Mexico that provides water level (storm surge) forecasts as well as
805 surface currents and surface salinity (Zheng and Weisberg, 2012).
- 806 ● South Florida Hybrid Coordinate Ocean Model (SoFLA-HYCOM) Shelf Circulation, developed by University of
807 Miami: its resolution spans from 1/25° to 2 m close to the coast and includes shelf areas, shallow embayment, and
808 the deep Straits of Florida (between Florida and Cuba) (Kourafalou et al., 2009).
- 809 ● LiveOcean, developed by the University of Washington - Coastal Modelling Group, mainly used for research
810 applications. It provides 3 days forecasts of currents, temperature, salinity and many biogeochemical variables in the

⁶³<https://tidesandcurrents.noaa.gov/ofs/ngofs2/ngofs.html>

⁶⁴https://tidesandcurrents.noaa.gov/ofs/tbofs/tbofs_info.html

⁶⁵https://tidesandcurrents.noaa.gov/ofs/cbofs/cbofs_info.html

⁶⁶https://tidesandcurrents.noaa.gov/ofs/dbofs/dbofs_info.html

⁶⁷https://tidesandcurrents.noaa.gov/ofs/gomofs/gomofs_info.html

⁶⁸<https://tidesandcurrents.noaa.gov/ofs/nyofs/nyofs.html>

⁶⁹https://tidesandcurrents.noaa.gov/ofs/sjofs/sjofs_info.html

811 US Pacific Northwest. The model horizontal resolution is 500 m in the Salish Sea and near the Washington coast,
812 growing to 3 km at the offshore boundaries (source: <https://faculty.washington.edu/pmacc/LO/LiveOcean.html>).

813 **10 Arctic Region**

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

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

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

839 Finally, perhaps one of the most important considerations for users is whether the data is readily available and easily
840 downloadable. The requirement for this varies greatly depending on the user, but those needing information on ships in the
841 Arctic, for example, will need quick access across potentially low bandwidth. All models related to Copernicus Marine Service
842 (neXtSIM-F, TOPAZ54, Arctic Ocean Biogeochemistry Analysis and Forecast, and Global Ocean Physical Analysis and

843 Forecasting by MOi) are available to download for free from the Copernicus Marine website, and there is a visualization tool
844 on the information page. Most other modelling systems have data for download and a visualization, although sometimes in
845 different places; these are the Barents-2.5km, NOAA ice drift, NOAA PSL, RIOPS, GIOPS, GOFS3.1, and RTOFS. The
846 systems from DMI and GOFS16 have a web page displaying the forecasts. As noted in Section 9, the CONCEPTS systems
847 (GIOPS, RIOPS, CIOPS) are available through the Meteorological Service of Canada Open Data platform (Data list /Liste des
848 données - MSC Open Data / Données ouvertes du SMC), including direct data access and geospatial web services. Data are
849 also available for download and visualization from the Ocean Navigator (<https://www.oceannavigator.ca/public/>). The
850 ArcIOPS, FIO-COM10 and NAVY-ESPC systems are well-documented in the literature, but it is hard to find a website that
851 states where/if downloading is available. The latter suggests some outputs are available for researchers if they register for a
852 login, but it is not stated how other users can access the data. Similarly, it is difficult to find information on how to access
853 outputs from the Met Office FOAM and its coupled data assimilation counterpart. For the global ECMWF model, some data
854 is available, but users must pay for other variables.

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

857 **10.1 Regional systems**

858 Several institutions are operating regional services in the Arctic

- 859 • The Arctic Ice-Ocean Prediction System ArcIOPS⁷⁰ (Liang et al., 2019) is managed by the Danish Meteorological
860 Institute (DMI). It employs the HYCOM-CICE model, covering the North Atlantic and Arctic Oceans with a
861 horizontal resolution of approximately 4-5 km in the Arctic and up to 10 km further south. The system is forced by
862 ECMWF weather forecasts and provides 144-hour forecasts twice daily at 00 and 12 UTC.
- 863 • The Danish Meteorological Institute (DMI) operates an ocean forecasting system utilizing the HYCOM-CICE
864 model⁷¹ (Ponsoni et al., 2023). This coupled ocean and sea-ice model covers the Atlantic Ocean north of
865 approximately 15°S and the Arctic Ocean, including Greenlandic waters. The system features a horizontal resolution
866 ranging from about 4-5 km in the Arctic regions to approximately 10 km further south. It is forced by atmospheric
867 data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and produces 144-hour forecasts
868 twice daily, at 00 and 12 UTC.
- 869 • The neXtSIM-F⁷² forecasting system (Williams et al., 2021) is a stand-alone sea ice model developed by the Nansen
870 Environmental and Remote Sensing Centre (NERSC). It utilizes the neXtSIM model, forced by the TOPAZ ocean

⁷⁰<http://www.oceanguide.org.cn/IceIndexHome/ThicknessIce>

⁷¹<https://ocean.dmi.dk/models/hycom.uk.php>

⁷²https://data.marine.copernicus.eu/product/ARCTIC_ANALYSISFORECAST_PHY_ICE_002_011/description

871 forecast and ECMWF atmospheric forecasts. The system assimilates OSI SAF⁷³ sea ice concentration products daily,
872 adjusting initial conditions and applying compensating heat fluxes to enhance forecast accuracy.

- 873 ● The National Institute of Polar Research (NIPR⁷⁴) in Japan provides Arctic Sea ice forecasts through its Arctic Sea
874 Ice Information Centre. These forecasts are disseminated periodically, with reports typically released in May, July,
875 August, and October each year. The May to August reports focus on predicting the opening dates of Arctic sea routes
876 and the sea ice distribution through September, while the October report forecasts sea ice distribution for the period
877 of sea ice extension from October onward.
- 878 ● The NOAA Physical Sciences Laboratory (PSL⁷⁵) operates the Coupled Arctic Forecast System (CAFS), an
879 experimental sea ice forecasting model. CAFS is a fully coupled ice-ocean-atmosphere model adapted from the
880 Regional Arctic System Model (RASM) and includes components such as the Weather Research and Forecasting
881 (WRF) atmospheric model, the Parallel Ocean Program (POP) ocean model, the Los Alamos Community Ice Model
882 (CICE), and the Community Land Model (CLM). All components run at a horizontal resolution of 10 km. The system
883 is initialized with the NOAA Global Forecast System (NCEP-GFS) analysis and Advanced Microwave Scanning
884 Radiometer 2 (AMSR2) sea ice concentrations. CAFS produces 10-day sea ice forecasts daily, with outputs posted
885 online at 2 UTC
- 886 ● The Regional Ice-Ocean Prediction System (RIOPS⁷⁶; Smith et al., 2021) is operated by the Canadian Meteorological
887 Centre (CMC). It employs the Nucleus for European Modelling of the Ocean (NEMO) coupled with the Los Alamos
888 Sea Ice Model (CICE). The system is forced by atmospheric data from the Global Deterministic Prediction System
889 (GDPS) and provides a forecast horizon of up to 48 hours. The model domain covers the North Pacific Ocean from
890 44N, the complete Arctic Ocean and the North Atlantic down to 26°N with a horizontal resolution of approximately
891 3-4 km over the Arctic Ocean. A fully-coupled forecast system called the Canadian Arctic Prediction System, that
892 uses RIOPS and a pan-Arctic atmospheric configuration at 2.5 km resolution is currently being reinstated (see Section
893 8 for details) following its retirement in 2021.
- 894 ● The TOPAZ4 system⁷⁷ is maintained by the NERSC. It utilizes the HYCOM model coupled with the Ensemble
895 Kalman Filter for data assimilation. The system is forced by atmospheric data from the ECMWF and provides a
896 forecast horizon of up to 10 days. The model domain encompasses the North Atlantic and Arctic Oceans with a
897 horizontal resolution of approximately 12.5 km.
- 898 ● The VENUS forecasting system (Yamaguchi, 2013) is operated by the Norwegian Meteorological Institute (MET
899 Norway). It employs the NEMO ocean model coupled with the LIM3 sea ice model. The system is forced by

⁷³<https://osi-saf.eumetsat.int/>

⁷⁴https://www.nipr.ac.jp/sea_ice/e/forecast/

⁷⁵<https://psl.noaa.gov/forecasts/seaice/about.html>

⁷⁶https://science.gc.ca/eic/site/063.nsf/eng/h_97620.html

⁷⁷https://data.marine.copernicus.eu/product/ARCTIC_ANALYSISFORECAST_PHY_002_001/description

900 atmospheric data from the AROME-Arctic weather prediction model and provides a forecast horizon of up to 66
901 hours. The model domain covers the Barents Sea and adjacent Arctic waters with a horizontal resolution of 4 km.

902 There are several characteristics to be highlighted in these systems:

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

919 10.2 Coastal systems

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

- 921 ● The coastal version of the DMI forecast model covers the Greenland region at 4-5 km resolution and uses HYCOM-
922 CICE like its regional version. It produces forecasts up to 144 hours ahead and is updated twice a day.
- 923 ● The Barents-2.5km model⁷⁸ covers the Barents Sea and Svalbard region (Röhrs et al., 2023). The ROMS model is
924 run at a spatial resolution of 2.5 km with an Arctic-specific atmospheric forcing, AROME-Arctic, providing forecasts
925 up to 66 hours ahead, and is updated every 6 hours.
- 926 ● The “storm surge” service⁷⁹ is a ROMS model run in barotropic mode, covering the northern North Atlantic, Barents
927 Sea, and Svalbard up to the entrance to the Arctic Basin. It uses the MEPS 2.5km atmospheric model for outputs,

⁷⁸<https://ocean.met.no/models>

⁷⁹<https://ocean.met.no/models>

928 providing forecasts for 120 hours updated every 6 hours. Its main purpose is to simulate sea level and storm
929 conditions.

- 930 • The CIOPS-E system (Paquin et al., 2024) is a $1/36^\circ$ (25km) resolution NEMO-CICE coupled model that is forced
931 by the High-Resolution Deterministic Prediction System atmospheric forcing and covers the East coast of Canada.
932 During its assimilation, it also uses RADARSAT satellite images. In addition to standard sea ice and ocean variables,
933 it outputs snow depth on sea ice and ice pressure at hourly frequency for the following 48 hours.

934 **11 Conclusions**

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

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

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

954 In this context, the OceanPrediction DCC Architecture (Alvarez et al., 2024a) offers a significant opportunity to promote the
955 development of robust ocean forecasting services worldwide. By providing a structured, modular framework for the
956 development of forecasting systems, it facilitates interoperability, scalability, and the integration of these systems. The concept
957 of Operational Readiness Level for Ocean Forecasting (Alvarez et al., 2024b), developed within the DCC framework, will

958 contribute to the quality of the system by supporting the application of Best Practices. These tools, when combined, have the
959 potential to accelerate the creation of new regional and coastal systems, while simultaneously enhancing the quality, reliability,
960 and user engagement of existing ones.

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

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1309 **Competing interests**

1310 The authors declare that they have no conflict of interest.

1311 **Authors contribution**

1312 MC designed, supervised, and validated the overall manuscript. All authors contributed to writing and revising the paper.
1313 Section 2 was additionally revised by EAF. EAF and MC conceptualized and wrote Section 1. WM wrote Section 3, SJ wrote
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