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STATE OF THE PLANET Discussions

A description of existing Operational Ocean Forecasting Services around the Globe

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Abstract. Predicting the ocean state in support of human activities, environmental monitoring and policymaking across different regions worldwide is fundamental and require numerical strategies that have to address their physical peculiarities. The Authors provide an outlook on the status of operational ocean forecasting systems in 8 key regions in the world 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 and the Arctic. Starting from the specific regional challenges to address, the Authors discuss on the numerical strategy and available operational systems, pointing out the straightness and the ways forward to improve the essential ocean variables predictability from regional to coastal scales, products reliability and accuracy. This compendium is a baseline to understand the worldwide offer, showing how the heterogeneity of the physical characteristics of ocean dynamics can be addressed thanks to a systematic and regular provisioning of predictions.

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1 Introduction

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

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

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

This paper aims to provide a comprehensive overview of the current state of ocean forecasting across various regions globally. By examining the technological, scientific, and operational aspects of forecasting systems in different parts of the world, we seek to identify both the strengths and gaps in existing capabilities. Furthermore, we explore the collaborative efforts and international initiatives aimed at enhancing global ocean forecasting, highlighting the importance of shared knowledge and resources in addressing the challenges faced by less-developed regions.

Through this study, we endeavour to shed light on the progress and ongoing challenges in the field of ocean forecasting, fostering a deeper understanding of the regional disparities and promoting efforts towards a more integrated and equitable global forecasting network.

The following sections describe, region by region, the situation in the different regions of the world.

2 West Pacific and Marginal Seas of South and East Asia

Ocean forecasting systems play a crucial role in providing timely and accurate information for a variety of marine activities, including navigation, fisheries management, offshore operations, and disaster preparedness. In the Western Pacific and Marginal Seas of South and East Asia (WPMSEA), these systems are particularly important due to the region's vulnerability to tropical cyclones, tsunamis, and other oceanic phenomena, as well as socio-economic development needs.To improve the effectiveness and accessibility of these systems for stakeholders throughout the region, it is essential to maintain investment in observation networks, modeling capabilities, and data sharing mechanisms. Several global observational frameworks operate under the umbrella of the Global Ocean Observing Systems (GOOS) within the WPMSEA, including NEAR-GOOS and SEAGOOS. Additionally, the region benefits from multiple global operational ocean forecasting systems, which contribute

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to a comprehensive understanding and prediction of oceanic dynamics (Figure 1). Several ocean forecasting systems are available, including the Global Real-Time Ocean Forecast System by National Oceanic and Atmospheric Administration (NOAA), the Global Ocean Physical Analysis and Forecasting Product by Mercator Ocean International, the Global and North Pacific Marine Forecasting by Japan Meteorological Agency (JMA), the Blue Link Ocean Forecasting Product by Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the HYCOM Consortium. These systems provide valuable information for ocean-related activities. These forecasts provide important information for decision-making and risk management in the WPMSEA. They include parameters such as wave height, sea surface temperature, currents, and sea level. Several other centers in China and Japan (Table 1) provide global operational forecast products as reviewed below besides regional and coastal products.

The Japan Coastal Ocean Predictability Experiments (JCOPE) system, developed by the Japan Agency for Marine-Earth Sciences and Technology (JAMSTEC) based on Pricenton Ocean Model, is a dynamic ocean monitoring and forecasting system (Miyazawa et al., 2009, 2021). Originally tailored for the western North Pacific at eddy-resolving resolutions, JCOPE is now extended to cover the global ocean with a new eddy-resolving quasi-global ocean reanalysis product, the JCOPE Forecasting Global Ocean (JCOPE-FGO). The model covers the global ocean from 75°S to 75°N except for the Arctic Ocean, with a horizontal resolution of $0.1° \times 0.1°$ and 44 sigma levels (Figure 2). The validation against observational data demonstrates JCOPE-FGO's effectiveness, while assessments using satellite data show its capability in representing upper ocean circulation (Kido et al., 2022). The significance of river forcing for accurately representing seasonal variability is emphasized by highlighting the inclusion of updated global river runoff in JCOPE-FGO and its significant impacts on near-surface salinity.

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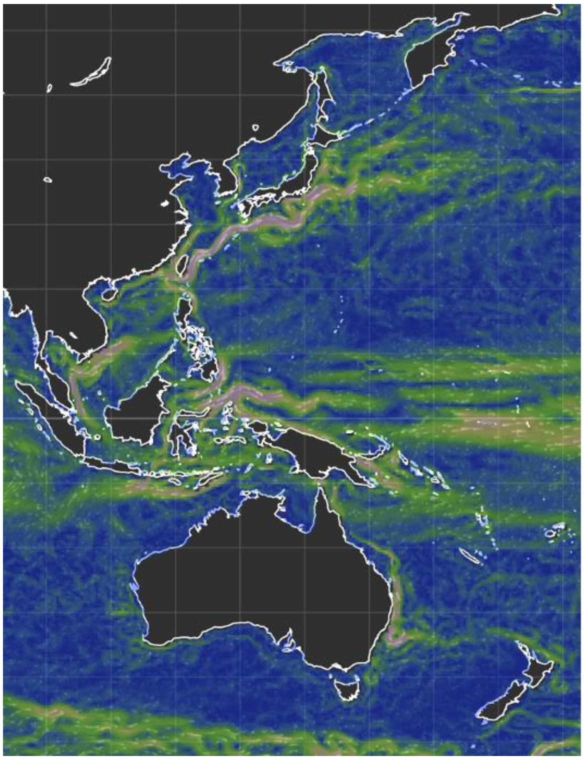

Figure 1: The surface currents and their magnitudes (shaded) in the WPMSEA region illustrate the dynamic characteristics of the current system in the area.

Table 1: Major regional/global models developed/used in the region.

Model	**Domain**	**Provider**	**Resolution**	**Availability**	**Reference**
MaCOM[1]	Global/regional/coastal	NMEFC	1/12º	Visual	Feng et al., 2024
LICOM[2]	Global	IAP	1/10º	Visual	Liu et al., 2023
FIO-COM[3]	Global	FIO/WESTPAC	1/10º	Visual/data	Qiao et al., 2019
BMKG-OFS[4]	Regional	BMKG	10 – 4.5km	Visual	
MRI.COM-jpn[5]	Regional	JMA	2 km	Visual/data	Hirose et al., 2019

[1] https://english.nmefc.cn/ybfw/seacurrent/WestNorthPacific
[2] http://project.lasg.ac.cn/licom/dist/index.html
[3] https://ioc-westpac.org/ofs/http://144.123.38.62:2018/#/
[4] https://peta-maritim.bmkg.go.id/ofs/
[5] https://www.data.jma.go.jp/gmd/kaikyou/kaikyou/tile/jp/index_subsanl.htm

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FRA-ROMS II[6]	Regional	FRA	1/10º	Visual/data	Kuroda et al., 2017
JCOPE[7]	Global/regional	JAMSTEC	1/10°-1/500°	Visual/data	Miyazawa et al., 2021
DREAMS[8]	Regional	Kyushu University	1/75°	Visual/data	Liu and Hirose, 2022
KOOFS/KOOS[9]	Regional	KHOA/KIOST	28km-100m	Visual	Park et al., 2015
BLUELINK[10] (Ocean Forecasting Australia Model (OFAM3)	Global/regional	CSIRO	~1/10º	Visual	Schiller et al., 2019

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[6] https://fra-roms.fra.go.jp/fra-roms/
[7] https://www.jamstec.go.jp/jcope
[8] https://dreams-c2.riam.kyushu-u.ac.jp/cgi-vwp/vwp_data.py?infof=vwp_DREAMS.cfg&dataf=&usr=&sid=&sidds=000001010001&passwd_dialog=0&lang=en&
[9] http://www.khoa.go.kr/oceangrid/gis/category/observe/observeSearch.do?type=EYS
[10] https://research.csiro.au/bluelink/global/forecast/

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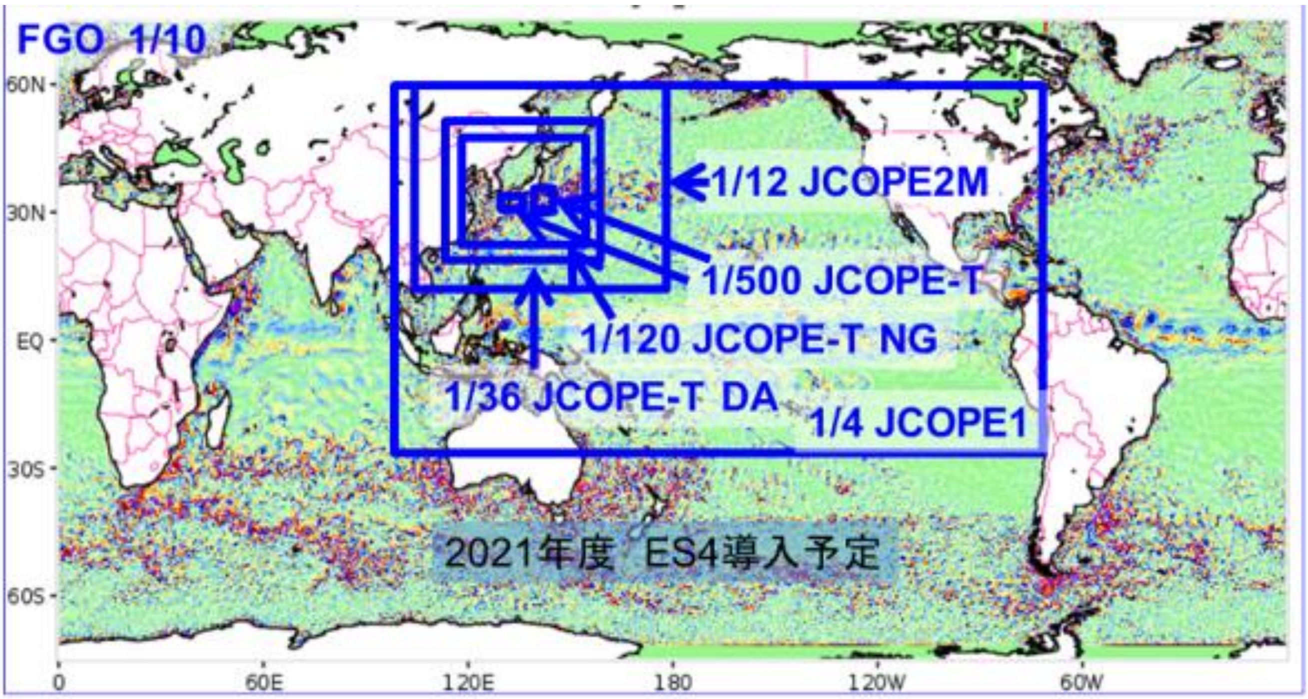

Figure 2: The downscaling of the JCOPE system from ~10km global to ~200m coastal, which is typical for several models including MaCOM operated in the region.

The Mass Conservation Ocean Model (MaCOM) model (Feng et al., 2024) is a newly established and operated global circulation model developed at National Marine Environmental Forecasting Center (NMEFC) in China. This model adopts a complete physical framework, the key feature of which is mass conservation, enthalpy conservation, salt conservation, and based on pressure coordinates. The MaCOM system is used from global (~ 10km) to coastal (~100m) forecasts and replaces several previously used models in NMEFC. The LASG / IAP Climate System Ocean Model (LICOM) Forecast System (LFS) is another forecast system from China that maintains a horizontal resolution of 3600×2302 grids (1/10°) and 55 vertical levels. Assessments indicate that LFS performs well in short-term marine environment forecasting. The root mean square errors (RMSE) for sea surface temperature range between 0.53-0.63°C, while for temperature profiles they range between 0.57-0.66°C. For salinity profiles, the RMSE ranges between 0.12-0.13 psu over leading 1-6 day forecasts (Zheng et al., 2023). The surface wave-tide-circulation coupled ocean model developed by the First Institute of Oceanography (FIO-COM) is another global model with an emphasis on tidal mixing (Qiao et al., 2019). The model is developed in close partnership with the Intergovernmental Oceanographic Commission of UNESCO Sub-Commission for the Western Pacific (WESTPAC).

Several centers in China, Indonesia, Japan, and Korea (Table 1) have also established operational ocean forecasting systems targeting short-term (up to 7-day) ocean current and wave variability around their territories. The products of the global ocean forecasting models provided from some operational centers are also utilized by many countries for their local interests. For example, with various data assimilation systems and ensemble forecasting techniques, JCOPE has been extensively utilized for nowcasting and forecasting of ocean conditions around Japan, demonstrating realistic depiction of temperature, salinity, and current fields. Moreover, the JCOPE system has been applied in various socio-economic studies, such as investigating radionuclide dispersion (Miyazawa et al., 2012, 2013) and Japanese eel migration (Chang et al., 2015). MaCOM ocean forecast systems also provides regional as well as coastal forecats on scales from kilometers to meters with various applications from oil spill forecasts and fishery to ice drifts and marine heat waves. Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) Indonesia has developed regional ocean forecast system of km scales and provides operational ocean forecasts of ocean temperature, salinity and wave information besides. There is a plan to improve the horizontal and vertical resolutions and an atmospheric-ocean-wave model. Two major Korean institutes, the Korea Hydrographic and Oceanographic Agency (KHOA) and the Korea Institute of Ocean Science and Technology (KIOST), 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. 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 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.

3 Indian Ocean

In the Indian region, four global scale forecast systems are regularly operating, while only two regional and one coastal forecasting systems are available for users. They are characterized by a lead time of up to 6 days, with options to access the data either by request or through web services of respective operational centers. In this section, a description of available models for the Indian Seas at various scales is provided.

3.1 Challenges in the region

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

Addressing these challenges requires a combination of improved observational networks, advanced modeling techniques, enhanced data assimilation methods, and increased computational resources. It also necessitates ongoing research and collaboration among oceanographic institutions, meteorological agencies, and scientific communities to enhance our understanding and predictive capabilities of the Indian Seas.

3.2 Forecasting system description

Among the global forecast systems identified for the Indian Seas, Real Time Forecast System (RTOFS) of US and Mercator Ocean System (MOS) from France are having the highest resolution of approximately 9.2 km for the Indian Seas. RTOFS system is based on the HYCOM model (Chassignet et al., 2009) and it is operational from October 2011. RTOFS uses atmospheric forcing from the Global Forecast System (GFS) delivered by the National Centers for Environmental Prediction (NCEP). It uses 3D multivariate data assimilation (Cummings, 2005) to assimilate in-situ profiles of temperature and salinity, satellite SST, SSH and sea-ice concentrations. MOS is based on NEMO model (Drevillon et al., 2023). It is forced with atmospheric variables from European Centre for Medium Range Weather Forecast (ECMWF) and it assimilates daily data of along track SSH from altimeters, and SST (e.g., AVHRR SST, RTG-SST and OSTIA) using Singular Evolutive Extended Kalman filter (SEEK) data assimilation (DA) method. Both RTOFS and MOS allow users to download the forecasts in real-time, which are updated routinely. Mercator provides excellent visualization dashboards for analysis and forecasts, and also there are specific bulletins issued through their website (http://bulletin.mercator-ocean.fr/).

Global INCOIS-HYCOM comes next in terms of resolution for the Indian Seas, with approximately 25 Km. It is forced with atmospheric variables from NCEP-GFS and assimilates AVHRR-SST, along track sea-level anomalies, in-situ profiles from various observing platforms using Tendral Statistical Interpolation Scheme (TSIS) DA method (Srinivasan et al., 2022). It produces 7 day forecasts, which are available to users on request. NCEP and INCOIS GODAS do not produce forecasts but produce analysis using the Modular Ocean Model (MOM) with a varying resolution of 25 km to 50 km. INCOIS GODAS variables are available to users through a live access server (http://las.incois.gov.in/las/UI.vm) and the NCEP GODAS variables are available through their website (https://www.cpc.ncep.noaa.gov/products/GODAS/).

Among the regional models available for the Indian Seas, regional INCOIS-HYCOM has the highest resolution of approximately 6.9 km, followed by regional INCOIS-ROMS with approximately 9.2 km resolution. Regional HYCOM is forced with atmospheric variables from NCEP GFS and uses the same DA method and variables described above in case of global HYCOM and takes boundary conditions from global HYCOM described earlier. Regional ROMS model from INCOIS uses atmospheric forcing from NCMRWF Unified model (NCUM) atmospheric model. It assimilates SST and vertical profiles of temperature and salinity from in-situ platforms using Local Ensemble Kalman Filter (LETKF) DA method. Data

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visualization and products from these models are available through web interface (https://incois.gov.in/portal/osf/osf.jsp) to users and data is made available to users on request.

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

The next Table 2 to Table 4 summarize the main characteristics of operational forecasting systems from Global to Coastal scale in the Indian Seas. Forecasts from different agencies are available through websites or on request.

Table 2: Major global models developed/used in the Indian Ocean.

Model	Domain	Resolution	Availability
HYCOM-RTOFS[9]	Global	9.2 km	Available through web
Nemo-Mercator[10]	Global	9.2 km	Available for registered users
INCOIS-HYCOM[11]	Global	25 km	Global data available on request. Provides boundary conditions to 1/16 Indian Ocean HYCOM
INCOIS-GODAS [12]	Global	50 Km near the equator to 25 Km near poles	Ocean analysis products are available to users through a live access server.
NCEP-GODAS [13]	Global	50 Km near the equator to 25 Km near poles	Available through web portal

Table 3: Major regional models developed/used in the Indian Ocean.

Model	Domain	Resolution	Availability
HYCOM-Indian Ocean[14]	Indian Ocean 45S-30N 20E-125E	6.9 km	Data available on request. Products available at web page
ROMS-Indian Ocean[15]	Indian Ocean 30s-30N 30E-120E	9.2 km	Data available on request and products available through web page.

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Table 4: Major coastal models developed/used in the Indian Ocean.

Model	Domain	Resolution	Availability
ROMS-coastal[16]	North Indian Ocean	2.3 degree	Data available on request. Products available at web page.

4 African Seas

The African Seas can be subdivided into six regions, based on distinct ecosystem characteristics: the Canary Current Large Marine Ecosystem (LME), the Guinea Current LME, the Benguela Current LME, the Agulhas-Somali Current LME, the Red Sea LME and the Mediterranean Sea LME. Aside from the Mediterranean Sea LME, that will be discussed separately, an overview of the landscape with respect to operational ocean forecast services will be provided below. Operational ocean modelling is a developing field, with limited capacity in most parts of Africa. Operational services in these regions therefore depend largely on core global products and vary in levels of complexity, from disseminating locally relevant information via monthly bulletins to limited area forecast models that use global products at their boundaries. While various types of ocean forecast services exist to support national priorities, two consortia have been developed through Global Monitoring for Environment and Security (GMES[11]) and Africa to provide more regional support for marine and coastal operations. These are Marine and Coastal Operations for Southern Africa and the Indian Ocean (MarCOSIO[12]) and Marine and Coastal Areas Management in North and West Africa (MarCNoWA). These platforms currently make use of global services for earth observations as well as marine forecast products that in some cases are optimized for local conditions.

4.1 Global Forecast Services

Short-term global ocean forecast services routinely utilized in African Marine and Coastal operations include:

- Earth System Science Organization - Indian National Center for Ocean Information Services (ESSO-INCOIS), Indian Ocean Forecasting System (INDOFOS) (Francis et al., 2013).
- Operational Mercator Global Ocean Analysis & Forecast, accessed via Copernicus Marine Services (CMEMS); https://doi.org/10.48670/moi-00016
- National Center for Environmental Prediction (NCEP), Global Real-Time Ocean Forecast System (RTOFS) (Garraffo et al., 2020).
- National Center for Environmental Prediction (NCEP), Global Forecast System - Waves (GFS)
- Australian Bureau of Meteorlogy, OceanMAPS (Brassington et al., 2012)

[11] https://gmes.rmc.africa/
[12] https://marcosio.org/

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- European Center for Medium-Range Weather Forecasting (ECMWF)

The global services above are utilized in various ways to support operational activities in African Seas. In many cases outputs from the global services are disseminated on local web portals, some countries provide bulletins in pdf format, some add local value to global services by developing and disseminating optimized metrics and there are a limited number of institutes that use the global services to force downscaled operational forecasts. Examples of the variety of use-types are provided in Table 5. Bandwidth is cited as the most common problem affecting the accessibility of global forecast services.

Table 5: Examples of which global forecast services are used (and how) in various African countries.

Country	Global Service	Local Service
Mauritius	CMEMS Mercator Global Analysis & Forecast	The Mauritius Oceanography Institute provides a web portal (affiliated with GMES and Africa) that outputs regional subset of global sea-state forecasts Monthly bulletins targeted at users from the marine and fisheries realm for monitoring purposes and is a source of information for researchers and the scientific community.
Kenya	ESSO-INCOIS, INDOFOS	The Kenyan Meteorological Department provides daily and weekly marine forecast bulletins.
Mozambique	INCOIS	Integrated Ocean and Information System for Mozambique, developed by the INCOIS project Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES)
Mozambique	NOA GFS-Wave	FEWS-INAM is a National Forecasting System developed by INAM in collaboration with Deltares. This system downscales from the NOA global service and provides information via a mobile app, text messages and daily bulletins.
South Africa	NOA GFS-Wave & CMEMS Mercator Global Analysis & Forecast	The South African Weather Service uses the NOAA global service, as well as currents from the CMEMS forecasts to run an operational regional and coastal wave and storm surge model (Barnes & Rautenbach, 2020). Additionally, they disseminate regional information based on CMEMS forecasts.
South Africa	CMEMS Mercator Global Analysis & Forecast	The South African Environmental Observation Network (SAEON) have developed downscaled limited area bay-scale forecast systems based on CMEMS ocean boundary conditions. Additionally, they have added regional value to CMEMS products: e.g., marine heat waves, location of the Agulhas Current (e.g. distance from

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		shore), SST anomalies in an operational service. The tools are currently being integrated into the web portal.

4.2 Regional Forecasts

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

- The IBI-MFC (Irish-Biscay-Iberian Marine Forecasting Center) Ocean Physics, Wave and biogeochemistry Analysis and Forecast products, operated by NOLOGIN and provided by the Copernicus Marine Service are suitable for use by regional services in North and Northwest Africa.
- INCOIS project: Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES) has developed an integrated high resolution regional ocean forecasting system that encompasses the ocean regions of Madagascar, Mozambique and Seychelles.
- The Integrated Red Sea Model (iREDS-M1) has been developed by the King Abdullah University of Science and Technology in Saudi Arabia. Its atmospheric and ocean (wave and general circulation) models are running on an operational basis to provide short-range forecasts for the Red Sea (Hoteit et al., 2021).
- The South African Weather Service (SAWS) provide regional wave, wave-current interaction and tide forecasts, downscaled from global services (refer to Table 3.1-1), none of which are assimilative (Barnes and Rautenbach, 2020). They also provide an empirically derived algorithm-based forecast of the sea-ice edge for METAREA VII (De Vos et al., 2021)
- The MarCNoWA (https://gmes.rmc.africa/) focuses on delivering Earth observation (EO) services on coastal and marine environments and fisheries:
  - Provision of potential fishing zone charts overlaid with vessel traffic,
  - Monitoring and forecasting oceanography variables,
  - Forecast of ocean conditions,
  - Oil spill monitoring,
  - Generation of coastal vulnerability indices, and Mapping of coastal habitats.

  Through a network of national stakeholders, regional fisheries and environmental bodies, academia, private sector and researchers, the project is to impact decision making in the beneficiary countries. It downscales Copernicus Marine products and provides forecasts (Forecasts - Global Monitoring for Environment and Security & Africa (rmc.africa))
- The forecasting system GCOAST (https://www.hereon.de/institutes/coastal_systems_analysis_modeling/research/gcoast/index.php.en) developed by HEREON is implemented at regional scale for the western coast of Africa. The GCOAST (Geesthacht Coupled cOAstal model SysTem, Staneva et al. 2022) is built upon a flexible and comprehensive coupled model system

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integrating the most important key components of the regional and coastal systems and, additionally, allowing including information from observations. The operational modeling system is developed based on a downscaling approach from the Copernicus Marine Service GLORIS forecast 1/12 global model, focusing on the western African coast. The wind-wave model is based in WAM. The atmospheric forcing is taken from ECMWF.

4.3 Coastal Forecasts

Operational ocean forecast services for African coasts include:

- The National Coastal Forecasting System for Mozambique (FEWS-INAM) provides 3-day ocean and meteorological forecasts in the form of daily bulletins and text messages to support operations at sea. It uses global NOAA GFS data to provide meteorological and wave boundaries, and GLOSSIS (https://www.deltares.nl/en/) for the storm surge boundary conditions. The forecasts include wave information, tide and surge water levels and atmospheric weather information. This system was developed by a consortium, including Mozambique's Met Office INAM31, Deltares, UK Meteorological Office and the DNGRH.
- The South African Weather Service (SAWS)38 provides higher resolution wave forecasts, optimized for key coastal regions as well as storm surge forecasts. The information is disseminated on their web portal.
- The SOMISANA (A sustainable Ocean Modelling Initiative: a South African Approach) has developed two limited area downscaled bay-scale operational forecast systems for key areas around the South African coastline, which are: i) Algoa Bay (Figure 3) and the ii) Southwest Cape Coast. The models run daily and provide 5-day forecasts of currents, temperature and salinity through the water column. The models are forced by the GFS atmospheric forecasts at the surface and by the Global Ocean Analysis and Forecasts system provided by Copernicus Marine Service at the lateral boundaries. The model outputs can be explored here: https://somisana.ac.za/explore/1 (Figure 3) and https://somisana.ac.za/explore/2. The validation reports are available for the two operational forecast models.
- Coastal and fluvial flood forecasting developed in response to the extreme storm surge and flooding events on the Kwa-Zulu Natal coast of South Africa by Deltares and the local municipality[13]. 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 European Center for Medium-Range Weather Forecasts (ECMWF) and the National Centres for Environmental Prediction (NCEP).
- The coastal forecasting system developed in response to extreme storm surge, waves and flooding events along the eastern coast of Ghana utilizes advanced modeling techniques and global forecast services. The coastal model employed in this system is GCOAST. The hydrodynamical model is based on SCHISM, which is coupled with wind wave model WWM. The system provides a 3-day forecast with hourly frequency. The coastal forecasting modeling platform ensures a flexible grid for the eastern coast of Ghana with a resolution ranging from 50 m in the estuaries

[13] https://publications.deltares.nl/EP4040.pdf

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up to 1 km. At the boundaries the model is coupled to Copernicus Marine products (GLORIS) . The input data for these models are taken from GLORIS CMEMS and from the European Center for Medium-Range Weather Forecasts (ECMWF) comprehensive approach ensures that stakeholders receive timely and accurate information to prepare and respond effectively to extreme events along the eastern coast of Ghana. Moreover, it integrates mangrove vegetation for nature based solutions (NBS).

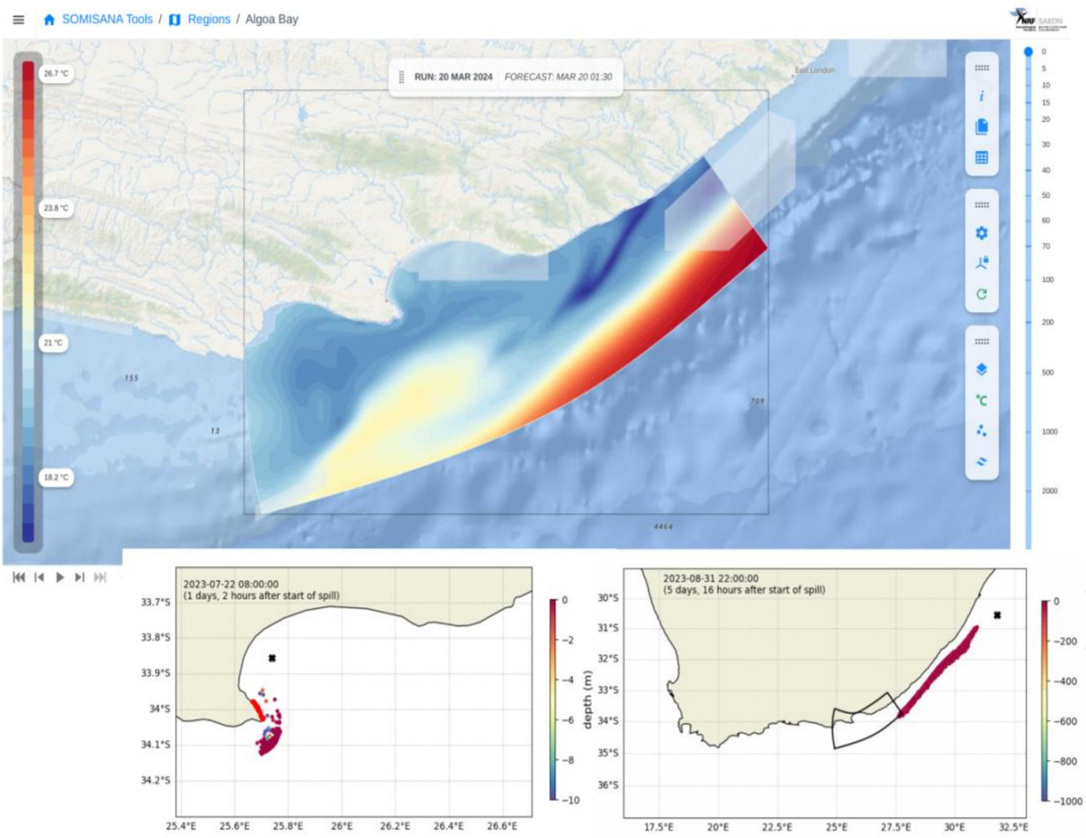

Figure 3: The web-portal of the bay-scale forecast system developed by the SOMISANA team in South Africa. The web portal allows users to explore the variables as well as to scrutinize various depth-levels of the forecasts. The insets show the oil-spill tracking functionality, developed using the OpenDrift software, that allows for the seamless integration of the global and regional, bay-scale forecasts in tracking the spill.

5 Mediterranean and Black Sea

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

- A general concept of operational oceanography was emerging worldwide.

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- The advent of new ocean monitoring technologies allowing for multiplatform systems, including both in-situ monitoring and satellite remote sensing, that in addition to the development of internet network connections started providing open data with a near-real time availability (Tintorè et al., 2019).
- The development of numerical modeling and prediction systems gave rise in 2000 to the release of the first ocean forecast of the Mediterranean Forecasting System which was providing regular and freely available 10-day predictions of the Mediterranean Sea dynamics with a spatial resolution of 7 km (Pinardi et al., 2003).
- The implementation of the first Black Sea nowcasting and forecasting systems which were developed during the first decade of 2000 in the framework of the ARENA[14] and of the EU FP6 ECOOP (European COastalshelf sea OPerational observing and forecasting system) projects.
- The Mediterranean scientific community started to get organized to establish a Mediterranean Operational Oceanography Network (MOON) which became in 2012 the Mediterranean Operational Network for the Global Ocean Observing System (MonGOOS[15]). Also the Black Sea Community, within the Global Ocean Observing System, has been established into the Black Sea GOOS[16].

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).

5.1 Regional Forecasting Systems

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

[14] http://old.ims.metu.edu.tr/black_sea_goos/projects/arena.htm
[15] https://mongoos.eurogoos.eu/
[16] https://eurogoos.eu/black-sea/

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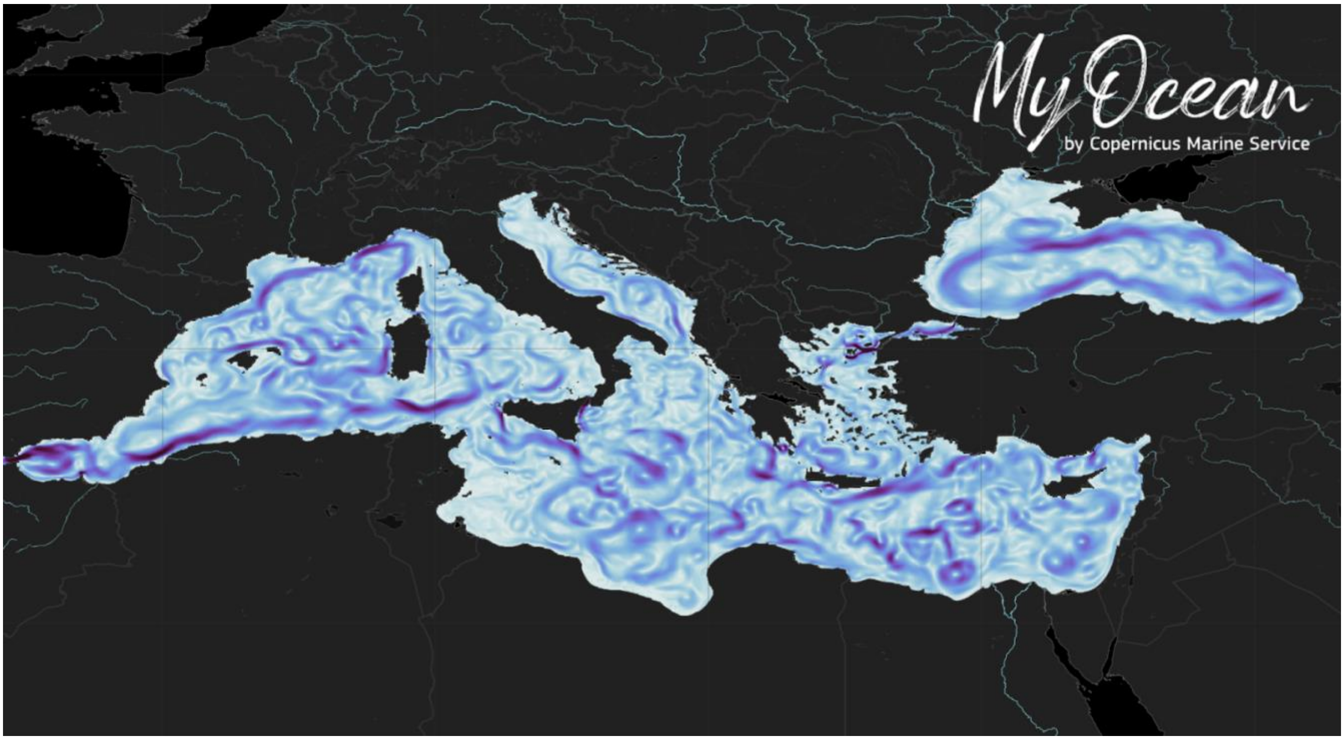

Figure 4: Mediterranean and Black Sea Forecasting Systems sea surface currents visualization as provided by the Copernicus Marine Service.

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

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

- A high-resolution Mediterranean and Black Sea system based on MITGCM (Massachusetts Institute of Technology General Circulation Model, Marshall et al., 1997) described in Palma et al. (2020). The system includes tides, is resolved at a 2 km resolution (and higher resolution in specific areas) and is nested in the Copernicus Mediterranean Analysis and Forecasting system. This system has been used as a basis to develop a 1/16° model to assess present and future climate in the Mediterranean Sea focusing on sea-level change - MED16 (Sannino et al., 2022).

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- The KASSANDRA[17] storm surge forecasting system for the Mediterranean and Black Seas which is based on the coupled hydrodynamic SHYFEM (Umgiesser et al., 2004) and wave (WaveWatchIII) models allowing for very high resolution in specific areas (Ferrarin et al., 2013).
- The Mediterranean Forecasting System[18] developed at INGV (National Institute of Geophysics and Volcanology, Italy) with 1/16° resolution, based on NEMO and implementing a data assimilation scheme.
- The physical and wave ocean system MITO (Napolitano et al., 2022) provides 5 days forecasts of the Mediterranean Sea circulation based on the MITGCM, is forced by the Copernicus Mediterranean physical and wave forecasting products to generate 5-day forecasts data at a horizontal resolution up to 1/48° degree.
- The POSEIDON[19] basin-scale Mediterranean forecasting system (~10 km resolution) ocean and ecosystem state, developed at HCMR (Hellenic Centre for Marine Research, Greece). This includes a hydrodynamic model, based on POM (Princeton Ocean Model, Blumberg and Mellor, 1987), which assimilates satellite and in situ data (Korres et al., 2007) and a biogeochemical model, based on ERSEM (European Regional Seas Ecosystem Model, Barretta et al., 1995; Kalaroni et al., 2020a, 2020b).
- The CYCOFOS wave forecasting system provides a 5 days forecast of the Mediterranean and the Black Sea (Zodiatis et al. 2018b) based on the WAM model and is forced by the SKIRON high frequency winds.

5.2 Coastal Forecasting Systems

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

HYDRODYNAMICS:

- The IBI[20] (Iberia-Biscay-Irish) Copernicus system provides operational analysis and forecasting data at 1/36º resolution implementing the NEMO model integrated with a data assimilation scheme.
- The “Sistema de Oceanographic Support System of the Port Authority”, SAMOA[21] (Álvarez Fanjul et al., 2018; Sotillo et al., 2019; Garcia-Leon et al., 2022), provides operational downstream services and a significant number of high-resolution forecasting applications, based on Copernicus Marine forecasting services and Spanish

[17] http://kassandra.ve.ismar.cnr.it:8080/kassandra
[18] https://medforecast.bo.ingv.it/
[19] www.poseidon.hcmr.gr
[20] https://marine.copernicus.eu/about/producers/ibi-mfc
[21] https://www.puertos.es/es-es/proyectos/Paginas/SAMOA.aspx

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Meteorological Agency (for atmospheric forecast), including 20 atmospheric models, 21 wave models and 31 circulation models. implements the ROMS[22] (Regional Ocean Modeling System) model at a resolution of 350 to 70 m.

- The WMOP[23] model (Juza et al., 2016; Mourre et al., 2018) based on ROMS is a downscaling of the Copernicus Mediterranean system with a spatial resolution of 2 km and covering the Western Mediterranean basin from the Strait of Gibraltar to the longitude of the Sardinia Channel. It is implemented by SOCIB (Balearic Islands Coastal Observing and Forecasting System) and is run operationally on a daily basis, producing 72-hour forecasts of ocean temperature, salinity, sea level and currents.
- A high-resolution numerical model, developed as part of an operational oceanography system in the frame of the "Sistema Autonomo de Medicion, Prediccion y Alerta en la Bahia de Algeciras" (SAMPA) project is implemented by Puertos Del Estado (Spain) providing operational ocean forecast data in the complex dynamical areas of the Gibraltar Strait and the Alboran Sea.
- The MARC (Modelling and Analyses for Coastal Research) and ILICO (Coastal Ocean and Nearshore Observation Research Infrastructure) are implemented using MARS3[24] model in the Bay of Biscay/English Channel/Northwestern Mediterranean Sea at 2.5 km horizontal resolution and nested in the Copernicus Global system.
- The Tyrrhenian and Sicily Channel Regional Model, TSCRM (Di Maio et al., 2016; Sorgente et al., 2016), is based on a regional implementation of POM at 2 km resolution and is nested into the Copernicus Mediterranean Analysis and Forecasting system.
- The Southern Adriatic Northern Ionian coastal Forecasting System, SANIFS[25] (Federico et al., 2017), is a coastal-ocean operational system based on the unstructured-grid finite-element 3D hydrodynamic SHYFEM model reaching a resolution of a few meters. It is a downscale of the Med-MFC physical product and provides short term forecast fields.
- The Aegean and Levantine Eddy Resolving Model, ALERMO[26] (Korres and Lascaratos, 2003), is based on POM implemented at 1/48° resolution and nested into the Copernicus Mediterranean Analysis and Forecasting system.
- The Cyprus Coastal Ocean Forecasting and Observing System, CYCOFOS (Zodiatis et al., 2003, 2008, 2018) is specifically developed to provide a sub-regional forecasting and observing system in the Eastern Mediterranean (including the Levantine Basin and the Aegean Sea). The latest system is forced by the Copernicus Med-MFC Physical forecasting system, implements POM at 2 km resolution to produce initial and open boundary conditions in specific locations.

[22] https://www.myroms.org/
[23] https://www.socib.es/?seccion=modelling&facility=forecast_system_description
[24] https://mars3d.ifremer.fr/docs/doc.basic.intro.html
[25] https://adri.cmcc.it/
[26] http://www.oc.phys.uoa.gr/mfstep/bulletin/

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- The TIRESIAS Adriatic forecasting system based on the unstructured grid 3D hydrodynamic model SHYFEM and representing the whole Adriatic Sea together with the lagoons of Marano-Grado, Venice and Po Delta (Ferrarin et al., 2019). It is a downscale of the Med-MFC physical product and provides 3-day forecast fields.

WAVES:

- The Copernicus IBI Wave forecast system (Toledano et al., 2022) is based on MF-WAM (Meteo-France WAM) implemented at 10 km resolution and produces wave forecast in the Western part of the Mediterranean Sea twice a day.
- The SAPO[27] (Autonomous Wave Forecast System) based on WAM model is implemented at several Spanish Ports (Spain) with a horizon of 72 h forecast and it is nested within the PORTUS forecast system, an operational wave forecast for Spanish Port Authorities.
- WAMADR setup of ECMWF WAM is implemented by the Slovenian Environment Agency for Adriatic and Central Mediterranean domain with a horizon 72 hours and spatial resolution of 1.6 km. The model is forced by a hybrid ALADIN SI and ECMWF surface wind product and is running daily.
- Several coastal and local wave applications providing wave information near the harbors, as well as boundary conditions for specific wave agitation inside the port applications, are using the SWAN model (Booij et al., 1999).

BIOGEOCHEMISTRY:

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

6 North-East Atlantic

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

[27] https://static.puertos.es/pred_simplificada/Sapo/d.corunia/sapoeng.html

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Copernicus Earth observation programme, which includes the Copernicus Marine Service component (CMS, https://marine.copernicus.eu/).

Due notably to the coordinating efforts provided by CMS over the last decade, the North-East Atlantic region is now well equipped in terms of operational marine forecasting services. Also, each segment of the North-East Atlantic coastline is included in at least one regional system, such that Global Forecast Services are seldomly used directly, except for the provision of boundary conditions to downstream forecast systems. An inventory of operational marine and coastal models around Europe was compiled out of a survey conducted in 2018–2019 among members of EuroGOOS and its related network of Regional Operational Oceanographic Systems (Capet et al., 2021), addressing the purposes, context, and technical specificities of operational ocean forecasts systems (OOFS). Here, we re-focus this analysis for the North-East Atlantic by excluding the Arctic, Mediterranean, and Black Sea basins from the original analysis. It should be noted that this inventory only includes OOFS actively reported to the survey and might therefore be incomplete. A further expansion of the North-East Atlantic OOFS inventory is expected from the OceanPrediction DCC Atlas.

Besides the three CMS regional forecast services, the inventory includes 35 others regional OOFS and 32 coastal OOFS, arbitrarily identified as systems with a spatial resolution below 3 km, and longitudinal and latitudinal domain extent below 5 degrees. Figure 5 provides a map of their domain extension, while some examples and specifications of OOFS from these three categories are given below in corresponding sections.

6.1 Regional Forecasts - Copernicus Marine Service

The major marine core service for the North-East Atlantic is provided by the CMS, and its three regional Monitoring Forecasting Centers (MFCs) dedicated to the Iberian-Biscay-Irish seas, European Northwestern Shelves, and Baltic Sea, respectively. In terms of modeling, each of these three MFCs is composed of dedicated components addressing ocean circulation (PHY), biogeochemistry (BGC), and wave dynamics (WAV). These systems operate under the coordinated umbrella of CMS and therefore benefit from homogenized protocols in terms of operational data production, validation, documentation, and distribution (Le Traon, 2019). Products and related documentation can be accessed through the central CMS portal, together with observational datasets including in-situ, remote sensing, and composite products for the Blue (physics and hydrodynamics), Green (biochemistry and biology), and White (sea-ice) ocean (Table 6). Operational data delivery is provided through online data selection tools and a variety of automatic protocols (e.g., MOTU, FTP, ERRDAP, OPeNDAP, WMS), which effectively enables a number of operational downstream services to depend directly on those core services. A catalog of such downstream usage and its potentialities is exposed on the CMS Use-Cases portal[28].

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

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Table 6: Principal characteristics of the three CMS regional core services for the North-East Atlantic region.

CMS Regional core services		Model Engine	Resolution	Forecast Time	Assimilated data
Iberian-Biscay-Ireland	PHY[29]	NEMO	1/36° / <1h	5d	Altimeter data; in situ temperature and salinity vertical profiles; satellite sea surface temperature
	BIO[30]	PISCES	1/36° / 1d	10d	-
	WAV[31]	MFWAM	5 km / 1h	10d	Significant wave height altimeter data; CFOSAT wave spectral data
European NW shelves	PHY[32]	NEMO	1.5 km / <1h	6d	Sea surface temperature; Vertical profiles of temperature and salinity; Along track satellite sea level anomaly.
	BIO[33]	ERSEM	7 km / 1d	6d	Sea surface chlorophyll

[29]https://data.marine.copernicus.eu/product/IBI_ANALYSISFORECAST_PHY_005_001/description
[30]https://data.marine.copernicus.eu/product/IBI_ANALYSISFORECAST_BGC_005_004/description
[31]https://data.marine.copernicus.eu/product/IBI_ANALYSIS_FORECAST_WAV_005_005/description
[32] https://data.marine.copernicus.eu/product/NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013/description?view=-&product_id=-&option=-
[33]https://data.marine.copernicus.eu/product/NWSHELF_ANALYSISFORECAST_BGC_004_002/description

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	WAV[34]	WAVEWATCH III	2 km / 1h	6d	-
Baltic Sea	PHY[35]	NEMO	2km / <1h	6d	Sea surface temperature; Vertical profiles of temperature and salinity
	BIO[36]	ERGOM	2km / 1d	6d	-
	WAV[37]	WAM	2km / 1h	6d	-

[34] https://data.marine.copernicus.eu/product/NORTHWESTSHELF_ANALYSIS_FORECAST_WAV_004_014/description
[35] https://data.marine.copernicus.eu/product/BALTICSEA_ANALYSISFORECAST_PHY_003_006/description
[36] https://data.marine.copernicus.eu/product/BALTICSEA_ANALYSISFORECAST_BGC_003_007/description
[37] https://data.marine.copernicus.eu/product/BALTICSEA_ANALYSISFORECAST_WAV_003_010/description

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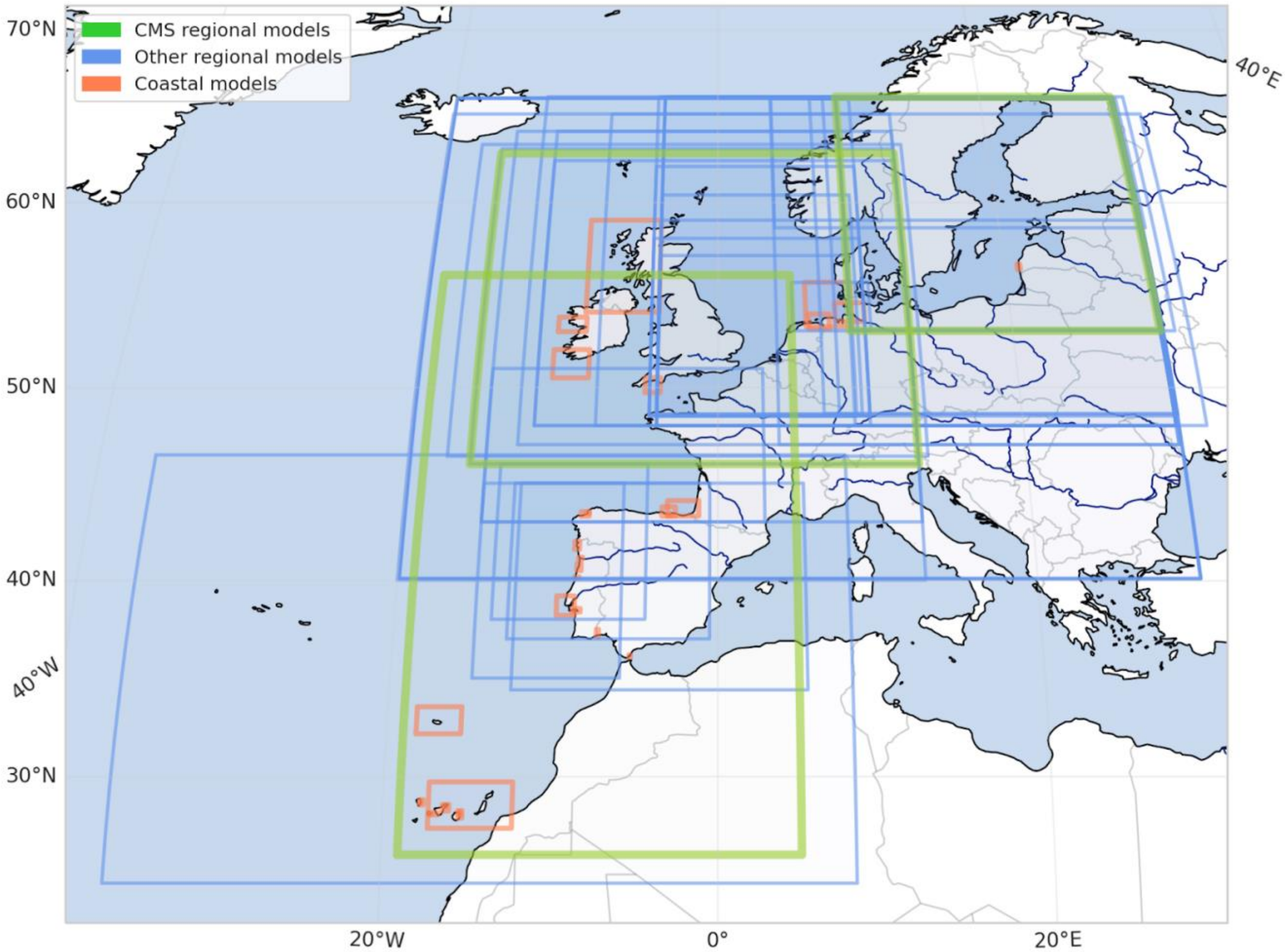

Figure 5: Domain external boundaries for OOFs in the North-East Atlantic. Inventory compiled from the 2018-2019 survey of the EuroGOOS coastal working group (Capet et al., 2021).

6.2 Regional Forecasts - Others

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

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6.3 Coastal Forecasts

32 coastal OOFSs are reported in the EuroGOOS CWG inventory for the North Sea, Baltic Sea, and European shelves, addressing circulation (68% of the coastal OOFS), biogeochemistry (29%), and wave dynamics (4%). Again, these OOFSs are mostly operated by public entities (although this is recognized as a potential bias in the survey, as discussed in Capet et al. 2021) and provide, in the vast majority, forecast data freely accessible to relevant users.

Among coastal OOFS, the usage of land and atmospheric forcing data from specific national sources is much more common than for regional systems, indicating that adequate products are available at local scales. Besides, several coastal system operators rely on their own atmospheric or hydrology model to obtain adequate boundary conditions. One could highlight that 15 of the 35 reporting coastal OOFS provide forecasts at a spatial resolution below 500 m, at least in some parts of their domain. In general, such systems also consider fine bathymetry, with a minimal water depth of under 5m (Figure 6).

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

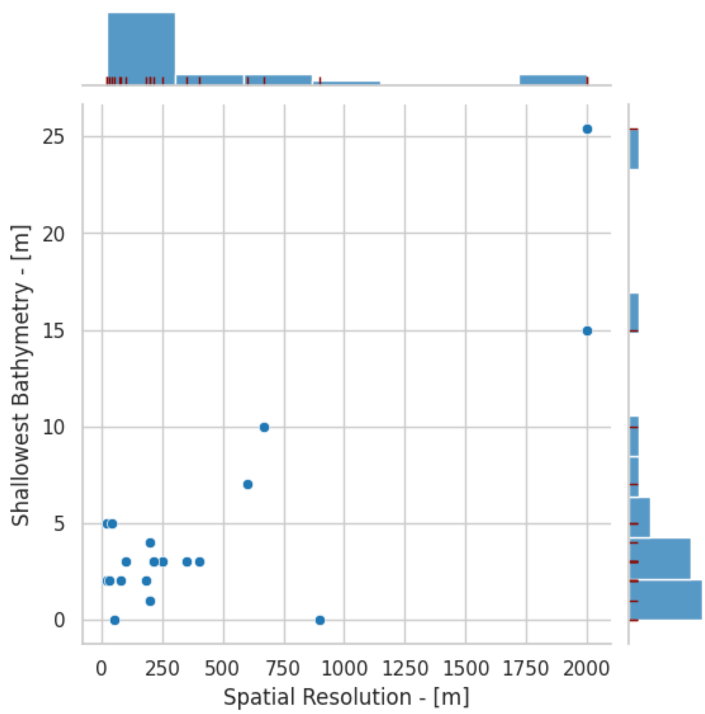

Figure 6: Joint and marginal distribution of the minimal water depth and spatial grid resolution, for all North-East Atlantic coastal model domains illustrated in Figure 5.

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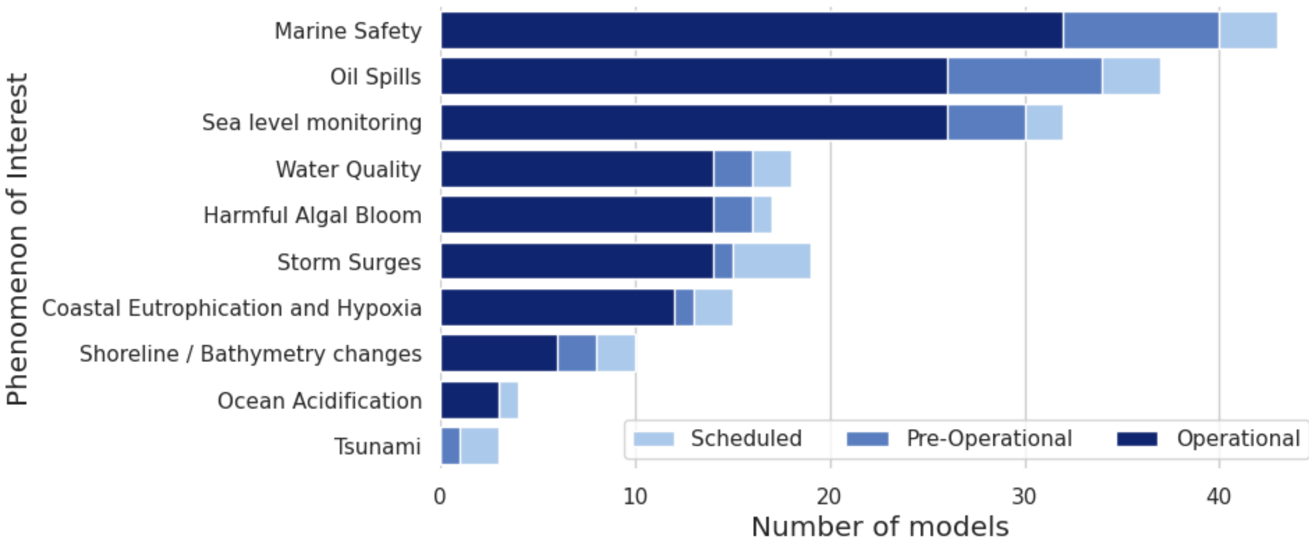

Figure 7: Number of regional and coastal models considered by their providers to be relevant for a proposed set of downstream sectorial applications and phenomenon of interest. Based on the 2018-2019 EuroGOOS CWG survey (Capet et al. 2021).

7 South and Central America

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

7.1 Regional Forecasting Systems

In Brazil, few regional (and coastal) forecast systems exist, considering the vast oceanic area under Brazilian jurisdiction (branded as Blue Amazon), which currently totalizes 4.4 million km2, approximately half of the Brazilian terrestrial area, with the possibility of reaching 5.7 million km2 in the future (Franz et al., 2021). The forecasting services results are not available for the public in general due to restrictions imposed by public-private partnerships and other constraints. The first operational ocean forecast system with data assimilation in Brazil was implemented in the Brazilian Navy Hydrographic Center (CHM) in 2010 based on the Hybrid Coordinate Ocean Model (HYCOM) and on an optimal interpolation scheme, developed by the Oceanographic Modeling and Observation Network (REMO) (Lima et al., 2013). Since 2014, CHM-HYCOM forecasts was initialized by the REMO Ocean Data Assimilation System (RODAS) (Augusto Souza Tanajura et al., 2014; Tanajura et al.,

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2020) based on the optimal interpolation scheme, which can assimilate SST analysis, along-track or gridded SLA and T/S vertical profiles. The ensemble members are chosen according to the assimilation day from a previous free run. The most recent CHM-HYCOM+RODAS configuration produces 5-day forecasts daily and encompasses the entire North, Equatorial, and South Atlantic with 1/12° horizontal resolution, to generate boundary conditions for a regional domain grid covering the METAREA-V (35.8°S-7°N, 20°W) with a horizontal resolution of 1/24°, both with 32 vertical hybrid layers. Other models are also employed operationally in CHM. ADCIRC is employed in Guanabara Bay, São Sebastião and Ilha Bela proximities and Sepetiba Bay, as well as in Santos and Paranaguá ports.

Regarding the Argentine Sea, the Modelling System for the Argentine Sea (MSAS) is used to model the barotropic component of the ocean state of the Southwestern Atlantic Continental Shelf. MSAS is based on the Coastal and Regional Ocean Community Model (http://www.croco-ocean.org). Dinápoli et al. (2020c, 2023) modified the source code to resolve the depth-averaged horizontal momentum and continuity equations, as well as consider spatially varying bottom friction. MSAS covers the Southwestern Atlantic Continental Shelf with a trapezoidal shape designed to avoid a significant number of land-points and ensure the regular spatial resolution of 8 km in both directions. Along the boundaries, the model is forced with tides and continental discharges, whereas in the interior of the domain, the ocean surface is forced by atmospheric pressure and surface wind stress (Dinápoli et al. 2021, 2020c, 2021, 2023). In addition, MSAS has been used to conduct several scientific studies on the barotropic nonlinear interactions in the region (Dinápoli et al., 2020b, 2020d), the tidal resonance over the continental shelf (Dinápoli et al., 2024), and the genesis and dynamics of the storm surges along the coast (Alonso et al., 2024). Recently, the Asynchronous Ensemble Square Root Filter (4DEnSRF, Sakov et al., 2010; Whitaker and Hamill, 2002) DA scheme was also incorporated as part of MSAS. The 4DEnSRF scheme is currently used to produce optimal initial conditions for the forecasts by assimilating tidal gauges and remote sensing observations. Because of the large and nonlinear impact of the wind uncertainty on the regional barotropic dynamics (Dinápoli et al., 2020a), an ensemble wind forecast is used. Dinápoli et al. (2023) used the 31-member ensemble from NCEP's Global Ensemble Forecast System, together with a set of perturbations of the tides. Since the atmospheric ensemble provides the wind field, rather than the wind stress, the former is estimated using the parameterization of Simionato et al. (2006). The incorporation of 4DEnSRF into MSAS forecasts, together an ensemble post-processing technique developed by Dinápoli and Simionato (2022), has improved the 96-hr forecasts by reducing the model bias and correcting the timing of the strong storm surges that affect the northern part of the Southwestern Atlantic Continental Shelf. It is important to mention that MSAS is running pre-operatively, and its solutions will be made public soon.

Relevant developments have been achieved with regard to wind wave modeling. The numerical model WAVEWATCHIII was regionalized and validated with direct observations from a number of buoys scattered in the Southwestern Atlantic Continental Shelf.

In Peru, a large effort in climate modeling has been undertaken in the 2000s to develop subseasonal forecasts and anticipate the significant socio-economic consequences of the El Niño Southern Oscillation (ENSO). The Geophysical Institute of Peru (IGP) has implemented recently in forecast mode a regional Earth System Model called IGP RESM-COW v1. This system released in December 2023 (Montes et al., 2023) is based on the CROCO ocean model (http://www.croco-ocean.org, Debreu et al., 2012) coupled to the WRF atmospheric model through the OASIS coupler (Craig et al., 2017) and now serves as an additional forecasting tool for establishing the recommendations by the ENFEN (Estudio Nacional del Fenómeno El Niño), a governmental body responsible for monitoring, studying, and predicting the El Niño phenomenon and its impacts on the country. The IGP RESM-COW v1 has a horizontal resolution of 12km for the ocean component, and 30 km for the atmospheric component. The domain covers the entire Peruvian territory and part of the eastern Pacific. The current implementation takes as input the forecasts of the NOAA CFSv2 global climate model that have been corrected using a combination of Reanalysis data (GLORYS12 outputs and the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) data), the climatological averages of the NCEP coupled forecast system model version 2 (CFSv2) and of a 22-years long simulation of the IGP RESM-COW v1 model. This allows forecasts of oceanic and atmospheric conditions to be made up to 7 months in advance (Segura et al., 2023). In addition, the Navy of Peru via the Dirección de Hidrografía y Navegación (Dihidronav) had implemented the WAVEWATCH III for representing the wave behavior at the northern, central and southern off Peru with a prediction up to 5 days[38]. This product is available for the scientific community and public interested in understanding wave conditions (https://cpps-int.org/index.php/wave-watch). Operation systems are also under development at IMARPE (Instituto del Mar del Peru, https://www.gob.pe/imarpe) based on the CROCO system, which targets the aquaculture industry in Central Peru region (Arellano et al., 2023). IMARPE and IGP also produce forecasts of ocean conditions at regional scale (Equatorial Kelvin wave amplitude in the Eastern equatorial Pacific) at subseasonal timescales based on shallow water models (Mosquera, 2014; Urbina and Mosquera, 2020).

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

In Colombia, the Colombia's Marine Meteorological Service (SMM, in Spanish), hosted by the Dirección General Marítima (DIMAR) as part of the Ministry of Defense, has co-developed over the last 8 years the Integrated Forecast System for Comprehensive Maritime Security (SIPSEM, in Spanish; Urbano-Latorre et al., 2023). SIPSEM is an ecosystem of climate services (Goddard et al., 2020) for meteocean applications, providing a suite of demand-driven and actionable information to ensure maritime safety and protect life at sea, while contributing to international regulations in the SOLAS, SAR, IALA, PIANC, IMO and WMO conventions. Focusing on the ocean component, SIPSEM uses CROCO involving different domains and nests, tailored for the different applications and coastal complexities. Application in regional scale in the Colombian Caribbean and Pacific employs a horizontal resolution equal to 9.16 km. Different CROCO forecasts systems are nested in

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

global forecasts produced by HYCOM+NCODA, Copernicus Global Ocean Physics Analysis and Forecast, and US Global Navy Coastal Ocean Model. They are forced with the Weather and Research Forecast Model (WRF) with 27 km of horizontal resolution nested in GFS forecasts. For wind-generated wave prediction, daily WAVEWATCH III (Tolman et al., 2002) forecasts are used for local and regional areas with 3.7 km and 18.5 km and are periodically calibrated by fine-tuning various model-parameters to best represent the local observations. SWAN (Booij et al., 1999) is also used in nearshore and ports applications. Some key SIPSEM forecasts are publicly available via a web portal[39] developed targeting the general user.

7.2 Coastal Forecasting Systems

Regional to coastal operational models for the Brazilian Coast started to be developed in 2018 by the Centre for Marine Studies (CEM), from the Federal University of Paraná (UFPR), in collaboration with MARETEC, a research center of the Instituto Superior Técnico (IST – Universidade de Lisboa) from Portugal, through the application of the MOHID modeling system. This initiative, called Brazilian Sea Observatory (BSO), was initially supported by the User Uptake program from CMEMS. In order to deliver high-resolution forecasts of the Brazilian coast, an operational modeling system was developed based on a downscaling approach from the Global Ocean forecast system at 1/12o resolution, focusing on the south-eastern Brazilian shelf, including estuarine systems with important port activities and large environmental protection areas. Nowadays, the operational modeling system include a model covering the south-eastern Brazilian shelf with a horizontal resolution of 1/24o, a model covering the coasts and adjacent shelf of the states of Santa Catarina, Paraná and São Paulo with a horizontal resolution of 1/60o, and high-resolution models (~120 m) for coastal systems (Florianópolis Bays, Babitonga Bay, and Paranaguá Estuarine Complex). The system is maintained by CEM/UFPR. Furthermore, an operational model was developed for the north of Brazil, encompassing the states of Amapá, Pará and Maranhão, and the Amazon River and Pará River estuaries, with a horizontal resolution ranging from 1/24o to 1/60o. The atmospheric forcing comes from the WRF model implemented by the Brazilian National Institute for Space Research (INPE) with 7 km of horizontal resolution. The operational models have a vertical discretization reaching about 1 m of resolution near the surface.

In Chile, efforts to implement operational forecasting systems were initially led by the Navy, with a focus on swell forecasting for the entire Chilean coast[40] or some keys sites[41]. These efforts have recently diversified to address issues around marine resource management (industrial and artisanal fisheries, aquaculture) and extreme events prediction. They are mostly based on the use of the CROCO system. As part of the national program COPAS Coastal, University of Concepcion is currently developing a forecast coupled systems based WRF, WAVEWATCHIII and CROCO to deliver 3 to 6 days forecasts of oceanic and weather conditions in the harbour of Coronel (378°S). The system is currently delivering operational products at 10 km resolution for the central Chile region (32°-38°S) in uncoupled mode (off-line)[42]. It targets a resolution of 2km in fully coupled

[39] https://meteorologia.dimar.mil.co/
[40] https://meteoarmada.directemar.cl/
[41] https://oleaje.uv.cl/index.html
[42] https://cdomportuario.oceanografia.udec.cl/

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mode and extended coverage for the ports of Arica (17.5°S) and Antofagasta (21.5°S). The national Fisheries Development Institute (IFOP) has recently developed an operational system called MOSA for the South part of central Chile focused on the inland seas of the Los Lagos and Aysén regions. It provides forecasts at a 3-day lead time based on CROCO at 1.2km. The atmospheric forcing is derived from a forecast run based on WRF at 3km with open boundary conditions from the Global Forecast System (GFS, Kalnay et al., 1996). Ocean boundary conditions are from Mercator and river run-offs from 35 point sources are used based on the FLOW products. Forecasts are provided on-line[43].

Besides these initiatives funded by the academic and public sectors, there are some private companies that also provide ocean and atmospheric forecasting for port operations in Chile. Siprol SpA[44] provides wave, wind, and waves forecasts. They also provide wave forecasting for Ecuador. Also, the company PRDW provides the Automated Wave Forecast System (AWFOS[45]), with 3hrs to 10 days forecasting using a mathematical model coupled with a global wave model wave for deep waters. PRDW also provides forecasting for various sites in South American countries. Finally, the Port of San Antonio, the first port in Chile in terms of port operations, is using models from the Direction of Port Construction (Dirección Obras Portuarias) in collaboration with the National Institute of Hydraulic of Chile (https://www.dop.pelcam.io/about). The wind forecasting is provided by the San Antonio Port Company (EPSA). In all the above, it is unknown the model used, validation and details in model configuration. Coastal applications employ 1.83 km and port applications employ a grid with resolution varying from 750 m to 150 m. The daily prediction system also involves an ensemble of CROCO forecasts, continuously calibrated using a pattern-based approach for the regional domain, and an additional local calibration for the coastal domains at higher resolutions.

8 North America region

9 Arctic region

In contrast to lower-latitude models, Arctic Ocean forecast models are focused on simulating the correct sea ice conditions, with the ocean below the mixed layer being of secondary importance on short time scales. There are 10 global models that are used for Arctic forecasting. There are also several regional models available, and a handful of coastal models (Table 3.1-6). Most models with Arctic forecasts are from national institutes that either represent large centers with dominant global forecasting platforms, have a large amount of Arctic research, or have an interest in maintaining a model due to having a border with the Arctic.

Given the focus around sea ice, there are several similarities across all forecasting systems, regardless of the domain. Firstly, all models must have a sea ice component. Almost all models use CICE as their sea ice model, with multiple sea ice thickness

[43] https://chonos.ifop.cl/mosa/?domain=chiloe
[44] https://siprol.com/
[45] https://awfos.prdw.com/

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categories. ArcIOPS uses the sea ice model in MITgcm, while VENUS uses the ice component of POM, the Mercator Ocean International model uses LIM2 and the Met Office FOAM and coupled models use CICE currently but will move to using SI3 in the future. The FIO-COM10 model uses the SIS sea ice model. The majority of forecasting models with an ocean component use HYCOM or NEMO for their ocean model; the exceptions are ArcIOPS (MITgcm), NOAA PSL (POP2), and FIO-COM10 (MOM5). Most of the models have an ice-ocean coupling and use an atmospheric forcing that has been created for a weather forecast; examples are those from ECMWF, the Regional Deterministic Prediction System, and NAVGEM. Four of the models identified - one regional model (NOAA PSL CAFS) and three global models (NAVY-ESPC, MetOffice coupled system and ECMWF) - are fully coupled to the atmosphere.

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

Finally, perhaps one of the most important considerations for users is whether the data is readily available and easily downloadable. The requirement for this varies greatly depending on the user, but those needing information on ships in the Arctic, for example, will need quick access across potentially low bandwidth. All models related to CMEMS (neXtSIM-F, TOPAZ4, Arctic Ocean Biogeochemistry Analysis and Forecast, and Global Ocean Physical Analysis and Forecasting by MOi) are available to download for free from the CMEMS website, and there is a visualization tool on the information page. Most other modeling systems have data for download and a visualization, although sometimes in different places; these are the Barents-2.5km, NOAA ice drift, NOAA PSL, RIOPS, GIOPS, GOFS3.1, and RTOFS. The systems from DMI and GOFS16 have a web page displaying the forecasts. The Gulf of St Lawrence model allows access of data, but it is not clear if there is an accompanying visual. The ArcIOPS, FIO-COM10 and NAVY-ESPC systems are well-documented in the literature, but it is hard to find a website that states where/if downloading is available. The latter suggests some outputs are available for researchers if they register for a login, but it is not stated how other users can access the data. Similarly, it is difficult to find information on how to access outputs from the Met Office FOAM and its coupled data assimilation counterpart. For the global ECMWF model, some data is available, but users must pay for other variables.

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

9.1 Global and regional Models covering the whole Arctic

- Most models are either coupled ice-ocean or coupled ice-ocean-atmosphere models. However, there are a few exceptions to this. The ECMWF model is also coupled to a wave model, while the NAVY-ESPC intends to include

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a wave model in the near future (Barton et al., 2021). The regional model neXtSIM-F is a standalone sea ice model which uses TOPAZ4 ocean and ECMWF atmosphere forecast forcings, and therefore only outputs sea ice variables. It is the only model to use a Lagrangian framework and a non-standard rheology. TOPAZ4 is the only model that has a version with a coupling to ECOSMO, a biogeochemical model, and additionally assimilates chlorophyll for input to this.

- The lowest resolution of the provided models is the regional ArcIOPS, at around 18 km. The ECMWF model is run at two resolutions: 9 km and 18 km. Most global models are around 1/12 degree (around 3-4 km in the Arctic), which is eddy-permitting everywhere and eddy-resolving in the deep basins. The Met Office coupled model is 1/4 degree, and the FIO-COM10 model is 1/10 degree. The NAVY-ESPC model is an outlier in that it is a global model but runs at very high resolution (1/25 degree), providing much more detailed forecasts than the other products. However, this data is not released to the public (detailed below). The resolution of the regional models is comparable to the global models.
- With the exception of RIOPS, which is run for 48 hours at hourly resolution, most models covering the full Arctic domain provide outputs for five to ten days, ranging from hourly output to daily output. NOAA ice drift and NAVY-ESPC provider forecasts for up to 16-days, the latter can also give information for up to 45 days but at lower resolution.
- Some models also provide additional sea ice variables; RIOPS, for example, and its global equivalent GIOPS, provide ice pressure, while TOPAZ4 provides sea ice type, albedo and snow depth. The VENUS, ECMWF, and MOi models include wave information and the RTOFS and MOi models additionally include MLD. TOPAZ4 running with ECOSMO outputs a number of biogeochemical variables including dissolved inorganic carbon, oxygen, nitrate, chlorophyll and phytoplankton.
- The VENUS model is unique in that it provides map-based forecasts for aiding ship navigation (generally in support of research cruises), and is deployed on demand rather than running continuously.

9.2 Coastal models

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

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

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- The storm surge model is a ROMS model run in barotropic mode, covering the northern north Atlantic, Barents Sea and Svalbard up to the entrance to the Arctic Basin. It uses the MEPS 2.5km atmospheric model for outputs, providing forecasts for 120 hours updated every 6 hours. Its main purpose is to simulate sea level and storm conditions.
- The Gulf of St Lawrence model is a 5km resolution NEMO-CICE coupled model that is forced by the RDPS atmospheric forcing. During its assimilation, it also uses RADARSAT satellite images. In addition to standard sea ice and ocean variables, it outputs snow depth on sea ice and ice pressure at hourly frequency for the following 48 hours.

It should be noted that in the Arctic, there are two other types of forecasts that are frequently used. The first is a statistical model rather than numerical; two examples that are detailed below are the ice drift forecast from NOAA, which uses satellite data of the present and uses a linear regression to predict the ice drift up to 16 days ahead in the Alaska coastal region. This is available as a visual on a 0.5 x 0.5-degree grid. There is also the Arctic Sea Ice Forecast produced by NIPR, which uses data from satellite passive microwave sensors to predict ice evolution up to seasonal (but includes a daily forecast); this is available as a forecast map on the website. The other type of forecast is ice charts that are derived from high-resolution SAR images and developed by experts; many users of Arctic forecasts rely on these for short-term, very local information. An overview is provided in Table 7.

Table 7: Principal characteristics of available OOFS in the Arctic region.

Model	Domain	Coupling	Resolution	Availability	Website and/or reference
ECMWF	Global	IFS fully coupled	1/10 degree	Free for member states; fee for commercial users	https://www.ecmwf.int/en/forecasts/datasets/set-i
GIOPS	Global	NEMO-CICE	12 km	Data and visual	**Smith et al., 2016**
MOI	Global	NEMO-LIM2	3.5 km	Data and visual	https://data.marine.copernicus.eu/product/GLOBAL_ANALYSISFORECAST_PHY_001_024/description
GOFS3.1	Global	HYCOM-CICE	3.5 km	Data and visual	**Metzger et al., 2014**
GOFS16	Global	NEMO-LIM2	3.5 km	Visual	https://gofs.cmcc.it/backend/public/gofs/short-description.html
Met Office coupled DA	Global	UM-JULES-NEMO-CICE	12 km	Not readily available	https://www.metoffice.gov.uk/services/data/met-office-data-for-reuse/model

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Met Office FOAM	Global	NEMO-CICE	3.5 km	Not readily available	https://www.metoffice.gov.uk/services/data/met-office-data-for-reuse/model
RTOFS	Global	HYCOM-CICE	3.5 km	Data and visual	https://polar.ncep.noaa.gov/global/data_access.shtml
NAVY-ESPC	Global	HYCOM-CICE-NAVGEM	1/25 degree	Limited availability as registered user	**Barton et al., 2021**
FIO-COM10	Global	MOM5-SIS with MASNUM wave	1/10 degree	Not readily available	**Shao et al., 2023**
ArcIOPS	Regional	MITgcm	18 km	Not readily available	http://www.oceanguide.org.cn/IceIndexHome/ThicknessIce; **Liang et al., 2019**
DMI	Regional and coastal	HYCOM-CICE	10 km	Visual	https://ocean.dmi.dk/models/hycom.uk.php; **Ponsoni et al., 2023**
neXtSIM-F	Regional	neXtSIM	7.5 km*	Data and visual	https://data.marine.copernicus.eu/product/ARCTIC_ANALYSISFORECAST_PHY_ICE_002_011/description; **Williams et al., 2021**
NIPR**	Regional	N/A	?	Visual	https://www.nipr.ac.jp/sea_ice/e/forecast/
NOAA PSL (CAFS)	Regional	POP2-CICE-WRF	10 km	Data and visual	https://psl.noaa.gov/forecasts/seaice/about.html
RIOPS	Regional	NEMO-CICE	3.5 km	Data and visual	https://science.gc.ca/eic/site/063.nsf/eng/h_97620.html; **Smith et al., 2021**
TOPAZ4	Regional	HYCOM-CICE (+ ECOSMO)	12.5 km	Data and visual	https://data.marine.copernicus.eu/product/ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_a/description
VENUS	Regional and coastal	IcePOM-WW3	2.5 km coastal	On demand	**Yamaguchi, 2013**

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Barents-2.5	Coastal	ROMS-CICE	2.5 km	Data and visual	https://ocean.met.no/models; **Röhrs et al., 2023**
Gulf of St Lawrence	Coastal	NEMO-CICE	5 km	Data	RDPS-CGSL
NOAA Ice Drift**	Coastal	N/A (free drift)	N/A; visual on 0.5 x 0.5 degree grid	Visual	**Grumbine, 1998**
Stormsurge	Coastal	ROMS barotropic	4 km	Data + warning	https://ocean.met.no/models

*Note that the resolution of a Lagrangian triangular mesh is not comparable to square grids, thus the output resolution is 3 km

**models use observed fields and advect them based on an atmospheric forecast rather than explicitly modelling the fields with sources and sinks

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Competing interests

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

Data and/or code availability

[OPTIONAL] This can also be included at a later stage, so no problem to define it for the first submission.

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