The Global Ocean Observing System

United Nations Educational, Scientific and Cultural Organization

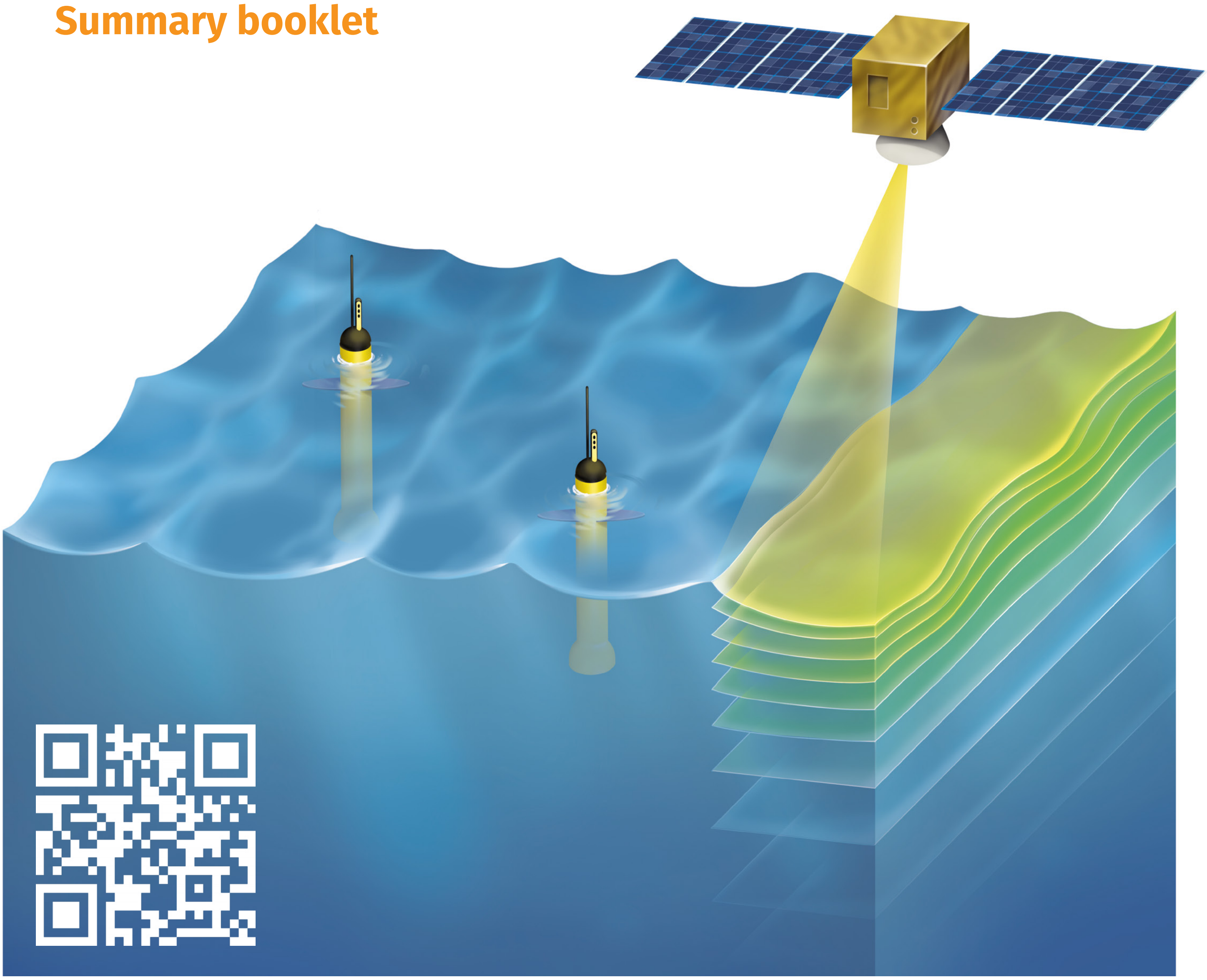
Intergovernmental Oceanographic Commission

WORLD METEOROLOGICAL ORGANIZATION

ETOOFS Expert Team on Operational Ocean Forecasting Systems

Implementing Operational Ocean Monitoring and Forecasting Systems

Summary booklet



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WITH THE SUPPORT OF MERCATOR OCEAN INTERNATIONAL

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The preparation of this summary has been coordinated by Mercator Ocean International in collaboration with ETOOFS (IOC/UNESCO) communication professionals and scientists. It is intended to serve as introduction to the GOOS Guide on Operational Ocean Monitoring and Forecasting Systems.

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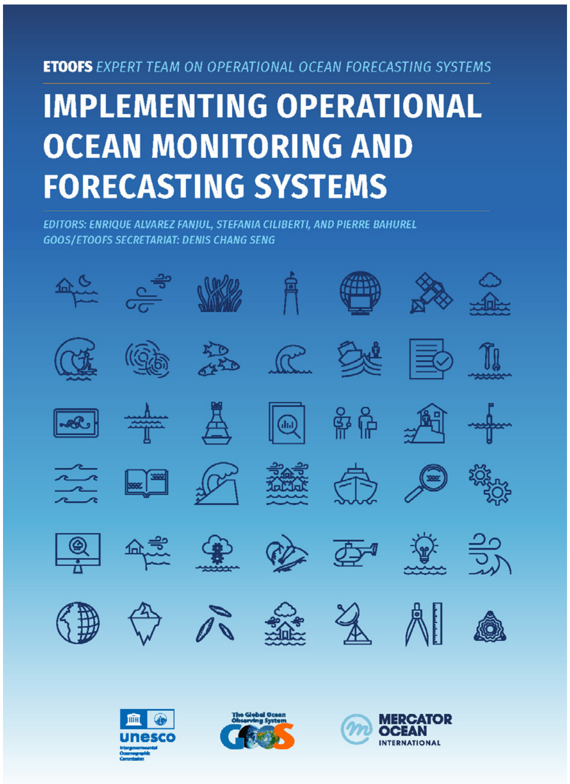
A Guide on Implementing Operational Ocean Monitoring and Forecasting Systems



At the request of the Intergovernmental Oceanographic Commission of the UNESCO (IOC-UNESCO) and the World Meteorological Organization (WMO), the Global Ocean Observing System (GOOS) and its Expert Team on Operational Ocean Forecasting Systems (ETOOFS) have published a guide on « Implementing Operational Ocean Monitoring and Forecasting Systems ». The present document is a summary of this guide, presenting its major characteristics in a synthesised way.

Through the publication of the guide, the Expert Team on Operational Ocean Forecasting Systems (ETOOFS) aims to promote the development of new marine forecasting systems around the globe along with the improvement of the existing ones. It provides an overview of the entire value chain of an operational ocean monitoring and forecasting system (OOFS) and presents international standards and best-practices for setting up an OOFS service.

This guide is intended to be a guideline and inspiration to professionals all around the globe, stimulating the reader to research deeper knowledge on this vast field. If this objective is achieved, this publication is expected to foster the generation of valuable information that will be used in decision making processes and, therefore, to advocate a wiser and more sustainable relation with our always generous ocean.

The publication is the result of the cooperation of 51 institutions from 18 countries worldwide, and the participation of 80 authors (here in alphabetical order):

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This summary follow the same structure as the guide and summarises each one of its chapters in one page.

TOWARD AN OCEAN FORECASTING CAPACITY P. 5

Operational oceanography has been driven by a great international momentum of scientists and engineers to build what is today a worlwide solid service infrastructure.

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Operational oceanography supplies routine and relevant products and information to its users along with relevant services driven by user requirements.

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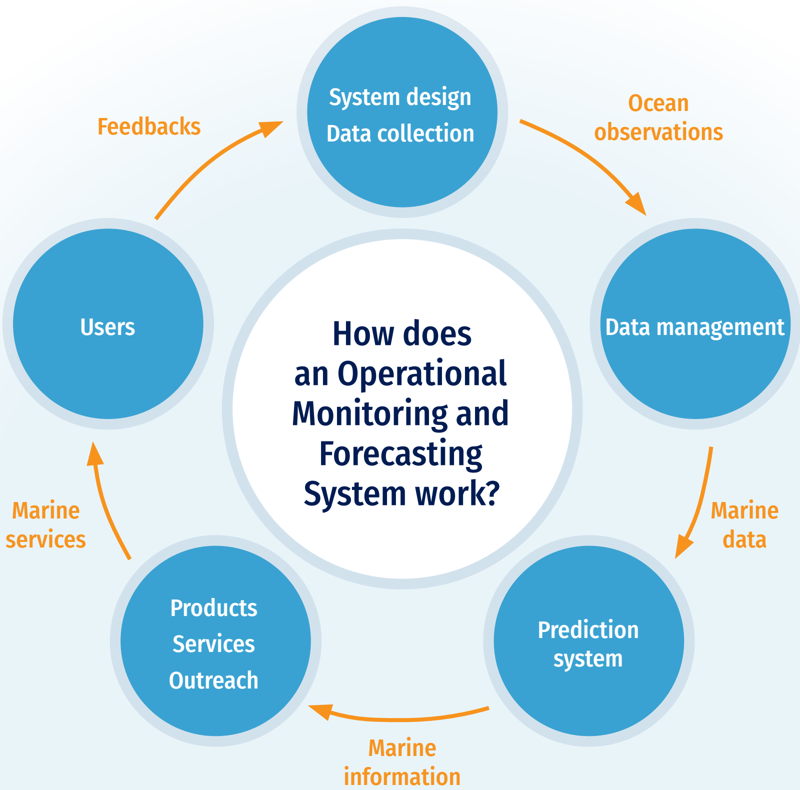
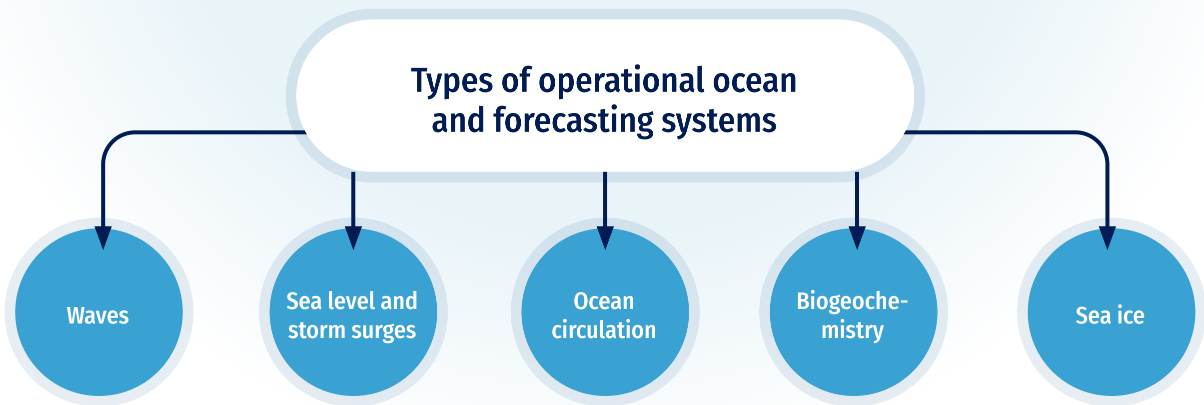
Introduction

What is operational oceanography?

Operational Oceanography is defined as the set of activities for the generation of products and services providing information on the marine and coastal environment. OO is designed to meet different societal, economical, scientific and other user needs. As defined by the EuroGOOS, there are two main pillars in OO services:

- the monitoring element, which focuses on the systematic and long-term routine measurements of oceans and atmosphere, and their rapid interpretation and dissemination;
- the prediction component, which uses ocean models to generate a variety of products that may be nowcasts (the most accurate description of the present ocean state provided by the analyses), forecasts (the future condition of the ocean for as far ahead as possible) or hindcasts (the most complete description of past states, provided by reanalysis).





Introduction

Given the importance of the ocean for humankind, its monitoring and forecasting has become a vital endeavor. Computing capacities, modeling, satellite and *in situ* observation networks have evolved to produce reliable data and information, which are used by decision-makers to promote an informed and sustainable management of ocean resources.

The ocean: key numbers

- **70%** of the Earth surface
- **50x** absorption of carbon compared to atmosphere
- **40%** of the world population concentrated on coastlines
- **15.7%** fish protein consumed worldwide
- **90%** of the world's trade

A science in constant evolution

The first scientifically successful ocean forecasting method was developed during World War II to facilitate plane landings. Since that early success, the technique has evolved into what it is today, a complex body of codes, data and technologies able to deal with the non-linear and chaotic nature of ocean processes, thanks to an increasing computing capacity.

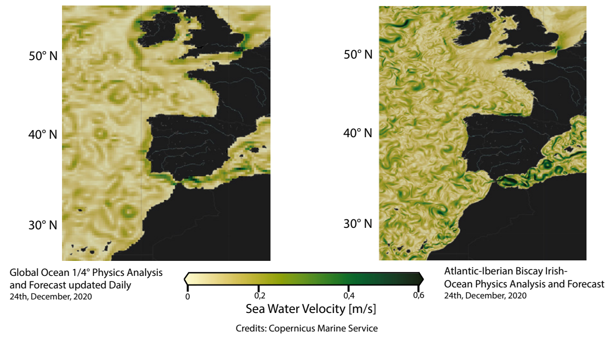
A science at the service of marine operations and applications

Ocean forecasting activities go beyond the execution of numerical models. Usually, the importance of these systems relies on their ability to fulfil the needs of multiple socio-economic sectors, often through dedicated applications, such as oil spill forecasting systems. Providing key information and standards on ocean forecasting services is crucial to foster their worldwide development and application to support the blue economy and sustained use of the ocean's resources.

Ocean Forecasting Value Chain

The core mission of the ocean monitoring and forecasting system consists of integrating the richness and variety of ocean observations to build a state-of-the-art digital description of the ocean environment, which is multivariable, consistent in space and time, reliable and immediately actionable by expert services.

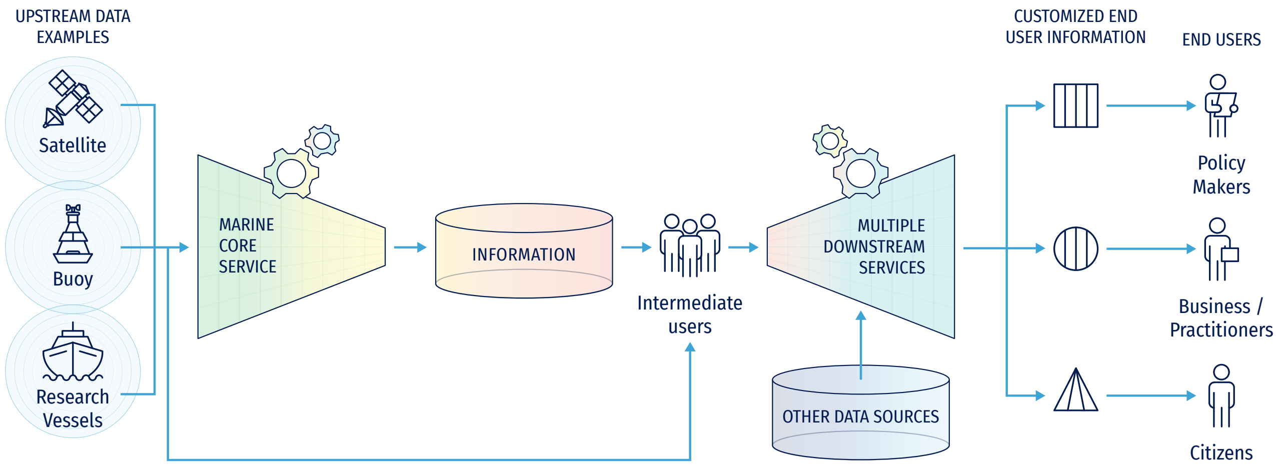
The numerical representation of the Ocean on the right panel is more accurate than on the left panel thanks to the increase of spatial resolution in the numerical models. The representation on the left is at a 1/4° resolution which allows to model the whole ocean. The right panel is at a 1/36° resolution which is mostly used in regional models.



Model resolution is constantly improving allowing us to better represent major ocean currents and fronts such as water velocity in the Iberian Biscay Irish Seas.

Building ocean physics model: data collection, assimilation and processes

Numerical models are based on the equations of the fluids. Additionally, to provide realistic forecasts, they depend on ocean observations. Today, these are taken both by in-situ instrumentation (fixed and drifting buoys, tide gauges, high frequency radars, etc.) and satellites (altimetry, radars, infrared imagery, etc.). Once this data is obtained, it is made available to the modeling system through a technique known as "data assimilation". This provides the forecast simulation with realistic "initial conditions", so the model can "advance on time" from the present ocean state.

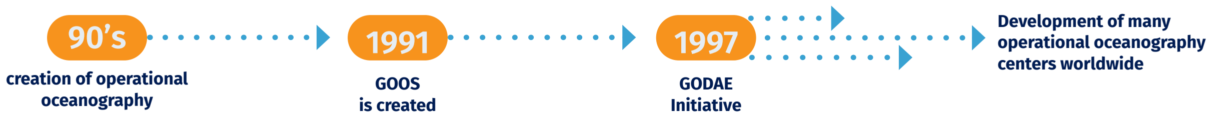


Motivation and Scope of Ocean Monitoring and Forecasting Capacity

Operational Ocean Forecasting Systems (OOFS) are amongst the main and more powerful tools to build the bridge between marine science and society needs, with a consistent and state-of-the-art digital depiction of the ocean environmental state. It took less than two decades to OOFS to emerge from science, gain realism and operational maturity, and convince users of their value; and this is not by chance if international cooperation was identified from the very first day as a key condition for success, being today the natural playground for the development of the OOFS capacity.

An international initiative and framework

Ocean forecasting took its modern form in the 90's, when in situ and satellite observations, numerical modeling and data assimilation were combined in an integrated approach. It was built through an international cooperation framework known as the Global Ocean Data Assimilation Experiment (GODAE). It played a leading role in building "a global system of observations, communications, modeling and assimilation that deliver regular, comprehensive information on the state of the oceans in a way that promote and engender the wide utility and availability of this resource for maximum benefit to the community". Most of the present-day ocean forecasting developments were initiated to respond to this international call.



Societal importance of ocean monitoring and forecasting system

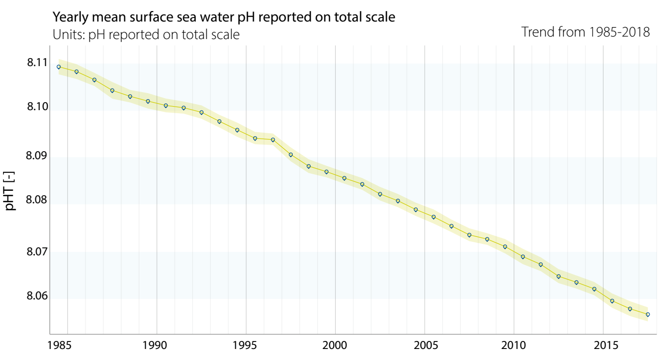
Operational services:
- Hazards: tsunamis, storm surges, high waves
- Costal services
- Navigation
- Energy

Climate:
- Ocean heat
- Sea level rise
- Sea ice

Marine ecosystem health:
- Ocean health
- Marine biodiversty conservation
- Food

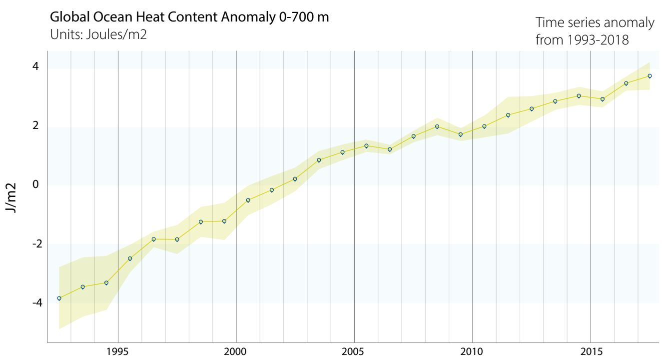

Oil spill emergency: the August 2020 incident in Mauritius.

Monitoring the global ocean acidification trend from 1985 to 2018 allows to understand the impacts of CO_2 emissions on the health of the marine ecosystem, such as coral bleaching.



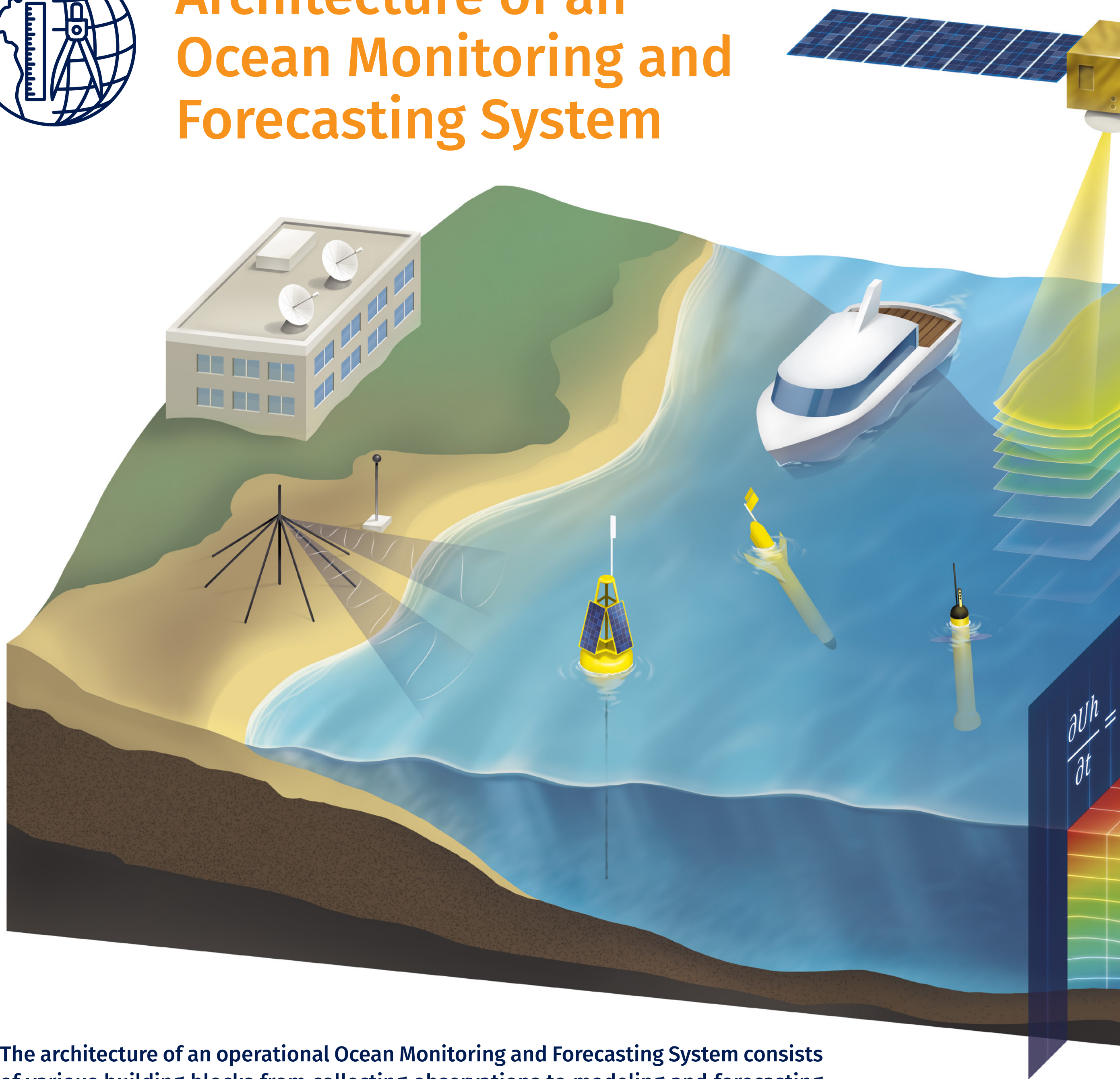
Annual global mean surface seawater pH derived from the Ocean Monitoring Indicator "Surface Ocean pH", showing an overall trend for decreasing pH and increasing acidification. Source: Copernicus Marine Ocean State Report 4.

Measuring the heat content in the ocean, i.e. the quantity of heat stored in the ocean is essential for understanding the changes in the Earth's climate. The ocean absorbs a large amount of the Earth's excess heat.



1933-2018 time series of global Ocean Heat Content anomaly in the upper 700 m of the ocean. Units are joules per square metre. Source: Copernicus Marine Ocean Monitoring Indicator.

Architecture of an Ocean Monitoring and Forecasting System



The architecture of an operational Ocean Monitoring and Forecasting System consists of various building blocks from collecting observations to modeling and forecasting the ocean state.

PRE-PROCESSING PHASE

1/ COLLECTING DATA ABOUT THE OCEAN STATE

In-situ and satellite data collected describe the state of the ocean, such as temperature or salinity.

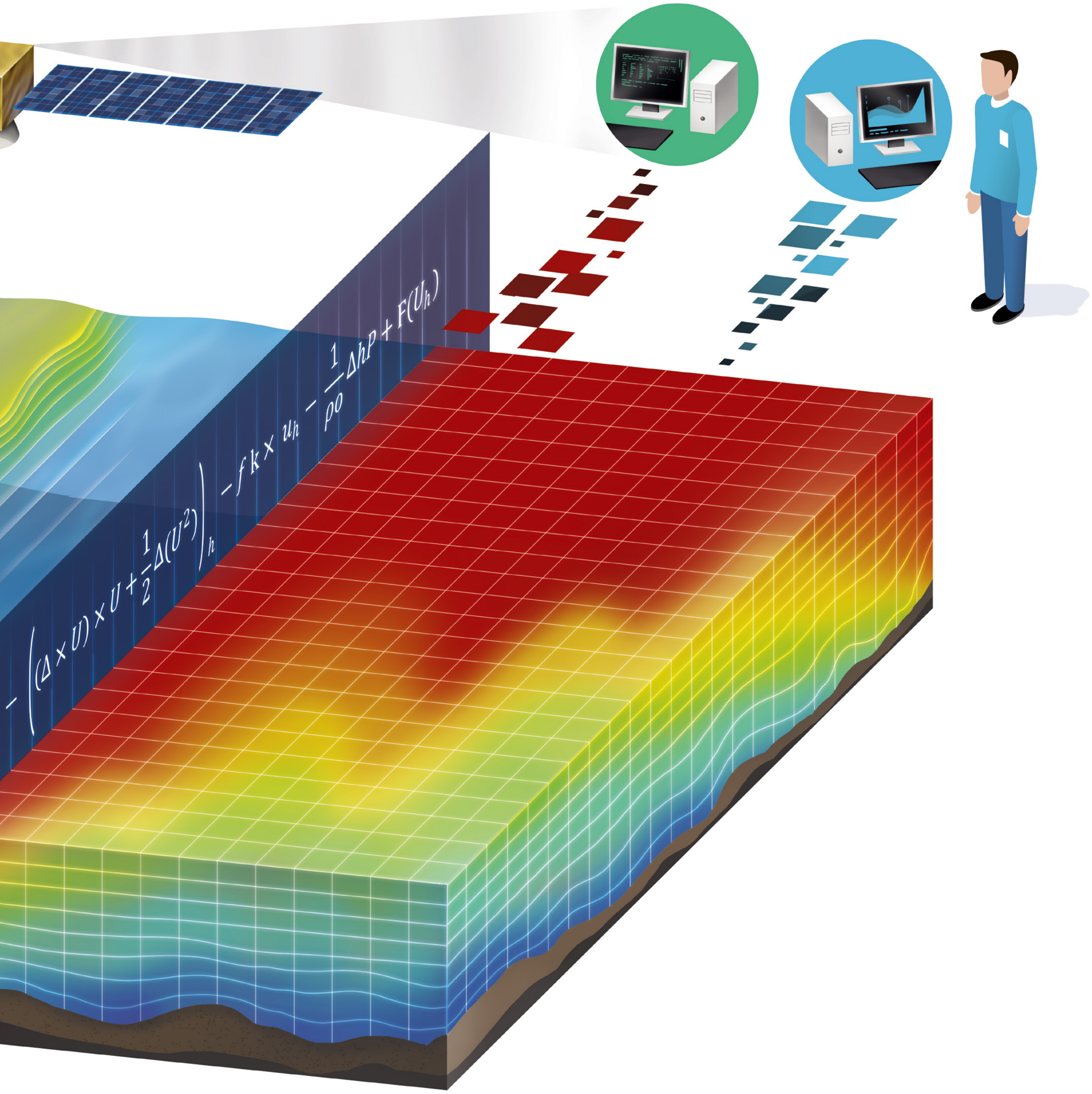
They are acquired thanks to different observation systems: satellites, buoys, ocean research vessels and underwater gliders to name a few.

2/ MODELING

Numerical ocean models employ specific mathematical formulae based on the fluid dynamics equations. They can describe the ocean state now and in the past and also predict the ocean state in the future. Such equations first need to be fed with initial and boundary conditions of the ocean state, i.e. start and surrounding information on the ocean state. Continuous equations have to be discretized, i.e. transferred from continuous formulae into discrete model grid formulae, in order to be solved by a computer: an adequate time and space step has to be selected.

Different techniques can be used such as:

- ensemble modeling where 3 or more related models analyze at the same time nearly the same process. Then, their slightly different results are averaged, and their difference is used to give an estimation of the error,
- coupled models in the situation where 2 model fields are run at the same time and can interact with one another.



INITIALISATION

3/ OBSERVATIONS ARE THEN ASSIMILATED

The model is constrained or guided by observations to stay as close as possible to the observations. This is called Data Assimilation.

4/ VALIDATION AND VERIFICATION

The model is evaluated against the available ocean observations to verify its reliability and quality.

FORWARD INTEGRATION AND POST-PROCESSING

5/ FORWARD INTEGRATION

The model can describe the ocean state in-real-time, in forecast or reanalysis mode.

6/ OUTPUT

An operational system routinely provides these predictions on a routine basis and with sufficient latency to support user's decisions.

7/ USER MANAGEMENT AND OUTREACH

Ocean products are then delivered to users at international and national or regional levels. User requirements (higher resolution, higher temporal frequency...) are taken into account to improve the products. A state-of-the-art service and user management has to be set up to ensure the quality of the service.

Temporal and spatial scales solved by Ocean Monitoring and Forecasting Systems

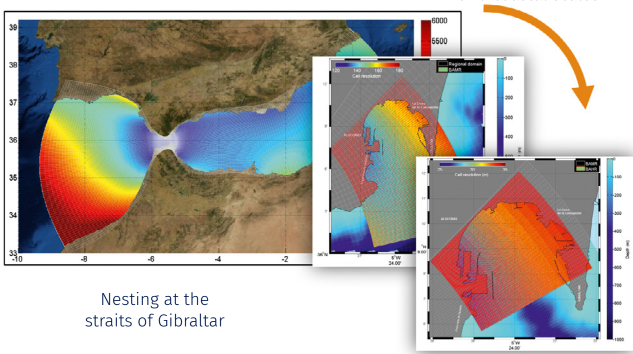
Operational Oceanography processes are described by a wide range of time and spatial scales. For example, the deep ocean and coastal ecosystems are interconnected. This means that, to represent the processes from one of them, you also need to consider the other. In order to describe the oceanic processes from both ecosystems simultaneously, one first needs to select the time and spatial scales that need to be solved, and also consider the computing power. In short, Ocean monitoring and forecasting activities span from nowcasts and few-days-ahead forecasts to climate modeling activities, in which simulation for the next several decades is required.

Range of Spatial scale

To achieve a realistic representation of the ocean state, there are processes that need to be mandatorily resolved at different spatial scales and some that can be neglected. For example, in waves modeling:

- In large-scale models, refraction is usually negligible
- At the coastal scale, refraction is a leading process

Therefore, different types of numerical models co-exist to be used depending on the scales to be solved.



Range of temporal scales

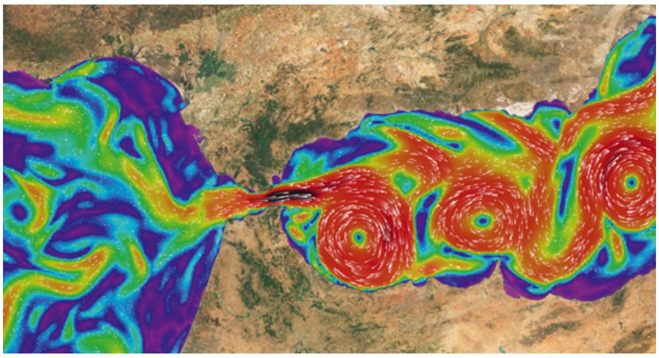
SHORT RANGE (NEAR-REAL-TIME, 10-DAYS FORECAST)

Short-range data provides knowledge of the essential ocean variables in real time or in the near future.

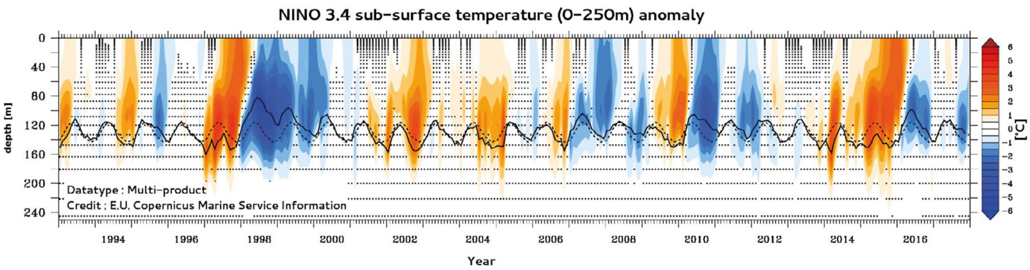
MULTI-YEARS

Long-range data simulation allows the analysis of long term trends and changes in the ocean state.

The graph below depicts the sub surface temperature anomaly (°C) over the 170°W-120°W 5°S,-5°N area for the period 1993–2018 from the Copernicus Marine Service. Niño sub-surface temperature anomaly is a good indicator of the state of the Central tropical Pacific el Nino conditions and enable us to monitor its phrase evolution.



An example of short term forerast: currents on the Gulf of Cadiz and Alborán sea, as depicted by a Copernicus Marine Service model.



Focus on coastal regions

Satellite observations provide invaluable information for monitoring the ocean state in coastal regions. However, they do not always provide the spatial and temporal precisions required by users. This difficulty can be solved by a modeling approach including a series of nesting ocean models: like Russian nesting dolls, nesting ocean models are used with a large scale model that feeds a higher resolution coastal model. Many models can be nested, depending on the required final resolution needed and the available computing resources.

Ocean circulation modeling

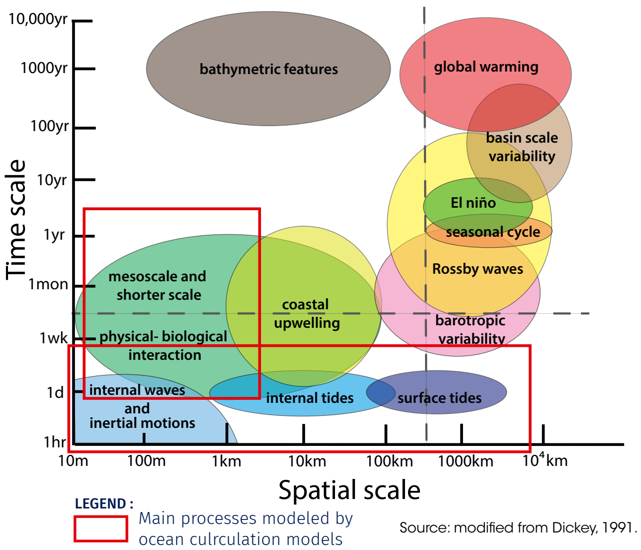
Modelling the ocean for prediction is a young discipline but with a strong theoretical baseline. Ocean forecasting began in the 1980s, thanks to a joint venture between Harvard University and the Naval Postgraduate School in Monterey, both in the United States, which completed the first successful forecast of ocean mesoscales in a limited ocean area.

What is an ocean circulation model?

The circulation modelling component represents one of the main cores of operational marine monitoring and forecasting systems: it provides an overall description of ocean physical essential variables (i.e. temperature, salinity, currents, sea surface height, etc.) for ocean predictions and for supporting climate studies. Ocean models are able to describe the sea state from global to coastal scales and to predict its variability and evolution in time (from short to mid-term to long-term). This is done by numerically solving a set of partial differential equations, based on an approximated version of the Navier-Stokes equations.

Various ocean circulation models

depending on the process, spatial and time scales:

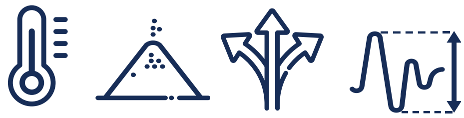


Source: modified from Dickey, 1991.

Key challenges

- Sea level rise
- Ocean temperature trend and anomaly
- Currents for ship routing, offshore energy development, search and rescue
- Water quality and oil spill monitoring

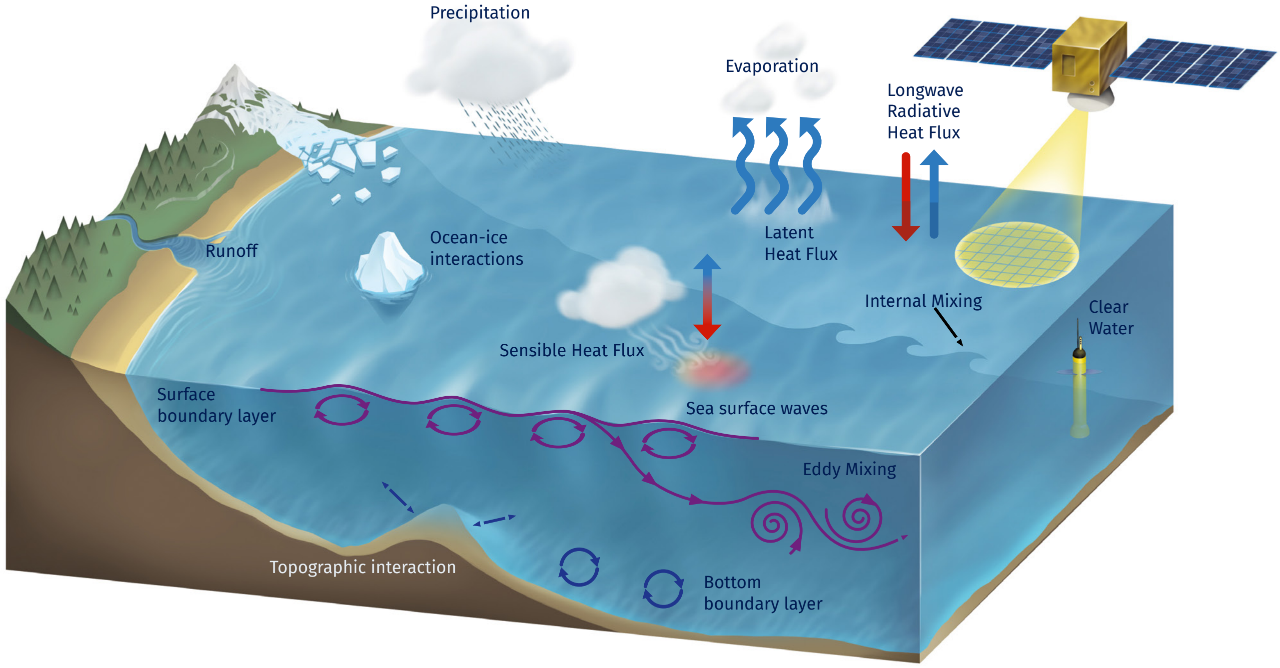
Related ocean variables



Modeling ocean circulation

The ocean is a system that interacts with other systems. We can identify:

- Connection with land: in particular with rivers and lakes which exchange freshwater flux with the ocean;
- Connection with the atmosphere: the ocean receives precipitation and returns evaporation.
- Connection with sea ice: the cycle of freezing/melting is associated with freshwater and salt fluxes and cannot be neglected;
- Connection with solid earth: heat and salt fluxes through the seafloor are small. For momentum instead, we express the kinematic boundary condition. Additionally, the ocean exchanges momentum with the Earth through friction.



Sea ice modeling

Sea ice forecasting systems provide users with a reliable estimate of the state of the ice cover and its temporal evolution. To achieve this goal, its core consists of coupled ocean-atmosphere models together with data assimilation to counteract errors due to the chaotic nature of the atmosphere-ocean-ice system.

Which processes are represented in ice modelling?

The physical processes simulated by sea ice models are commonly split into two: vertical processes, related to thermodynamic growth and melt, and mechanical and dynamical processes giving rise to horizontal movement of ice.

The ice is generally modelled as a continuum, with the sea ice moving in a horizontal plane, subject to both external and internal forces. The dynamic evolution of the sea ice cover is described using two continuity equations and the momentum equation. The thermodynamic evolution is modelled within each column of the grid and is modelled as a heat diffusion process within the slab of sea ice.

Modeling sea ice

Modelling sea ice for forecasting requires:

- Sea ice concentration from satellite observations for initialization, together with newer sea ice thickness and drift to improve the predictive capabilities
- Numerical model, based on a) continuity equations for ice and open water, b) momentum equation and c) thermodynamic equation
- Definition of the sea ice rheology, as relationship between the internal stress and resulting deformation

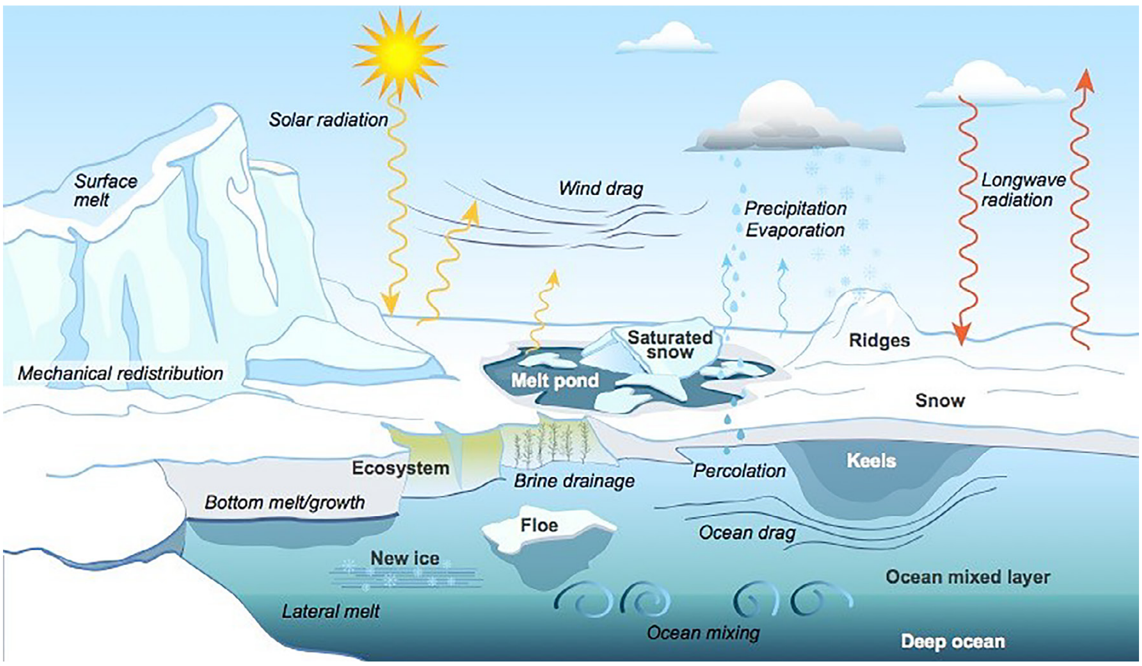
Key challenges

- Arctic warming
- Oil and gas exploration
- Icebreaker cruises
- Navigation and shipping industries

Related ocean variables

- Sea ice concentration (SIC)
- Sea ice thickness (SIT)
- Sea ice drift velocity in x- and y-directions (SIUV)
- Snow depth (SNOW)
- Sea ice age
- Sea ice albedo (SIALB)
- Sea ice temperature

Sea ice interacts with the atmosphere through heat, moisture, and momentum exchanges. Momentum transfer between ice and atmosphere happens through wind stress at the surface of the ice. This is the main driver of ice movement and exerts a drag on the atmosphere, slowing down the wind;



A CICE Consortium graphic of sea-ice physics illustrates the complexity and breadth of variables at play (From Los Alamos National Laboratory)

Sea level and storm surge modeling

Many natural phenomena can cause the sea to rise and fall, such as wind, air pressure, celestial gravity, earthquakes, etc. The sea level changes caused by different phenomena have different periods. For example, wind waves have a period of several seconds, tsunami waves of few minutes to tens of minutes, and the period of storm surge and astronomical tide is about several hours to several days. Among them, the storm surge brings huge economic losses and risks to coastal countries every year. In order to reduce the impact of storm surge disasters on coastal residents, understanding and forecasting storm surge have always been an important objective for marine forecasters.

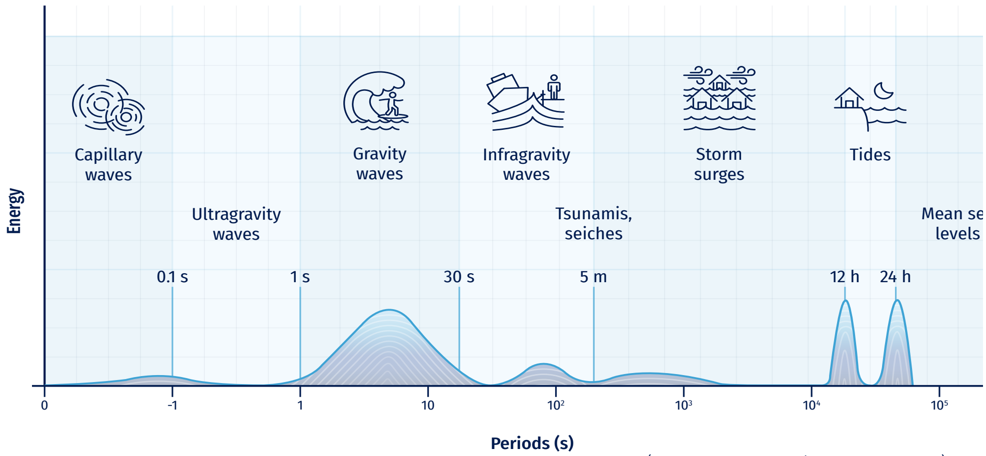
Key challenges

- Coastal marine disaster prevention
- Flooding
- Sea level rise
- Meteotsunami

Related ocean variables

Sea surface stress

Sea surface height



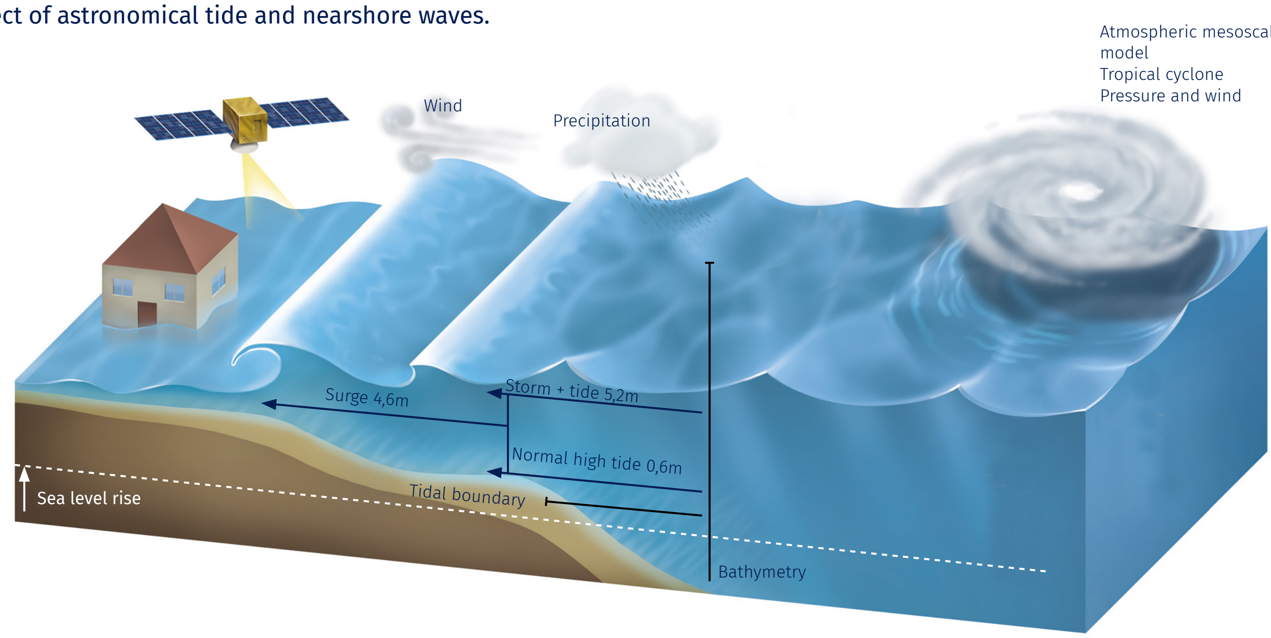
Frequencies and periods of the vertical motions of the ocean surface (adapted from Pérez et al., 2013).

What are sea level and storm surges?

Storm surge refers to the phenomenon of abnormal water level rise in a coastal or inland body caused by strong atmospheric disturbances, such as tropical cyclones (typhoons, hurricanes), extratropical cyclones, strong winds from cold fronts, and sudden change in atmospheric pressure. As a complex coastal dynamic process of major coastal marine disasters, storm surge has received much attention by major affected countries all over the world. Storm surge disasters are mainly caused by the abnormal water level rise and by flooding. The disaster causing factors include not only the storm surge, but also coupling with the effect of astronomical tide and nearshore waves.

Modeling sea level and storm surges

Storm surge refers to strong atmospheric disturbances, such as tropical cyclones (typhoons and hurricanes), extratropical cyclones, strong wind due to cold fronts, and sudden changes in atmospheric pressure inducing abnormal water level rise combined with nearshore wave setup. Models are generally based on the two-dimensional shallow water equation to compute the water level and velocity. According to different modelling purposes, the storm surge model can be divided into: i) storm surge model without tide; ii) storm surge model including astronomical tide; and iii) storm surge flooding model considering inundation.

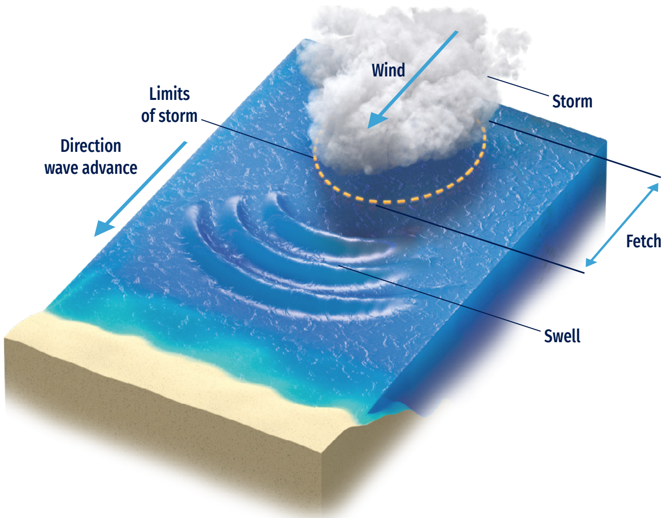


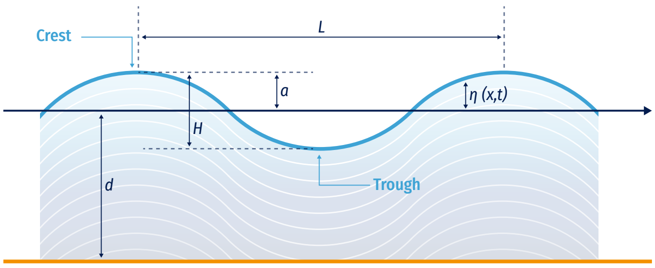
Wave modeling

In the last decade, the worldwide seas were hit by severe storms, which caused serious damages in offshore and coastal zones, and attracted public attention on the importance of having reliable and comprehensive wave forecasts, especially when extreme events occur. Human activities, such as offshore wind power industry, oil industry, and coastal recreation also necessitate regular operational sea state information with high resolution in space and time. Extreme waves can cause serious impacts over coastal environments and infrastructures: the design of coastal and offshore structures requires a reliable estimation of maximum wave height. In this context, wave forecasting products are of crucial importance.

What are waves?

The wave variable represents one of the fundamental bases of meteo-oceanographic knowledge, due to its energy and interactions with natural and human activities in open and coastal areas. Therefore, it is important to have a good quantification of wave characteristics, either from a statistical (long-term or multi-year / hindcast databases) or predictive (short- to medium-term / forecast strategies) approach.





Characteristics of a 2D linear water wave

Key challenges

- Coastal erosion
- Flooding
- Navigation
- Operations at sea

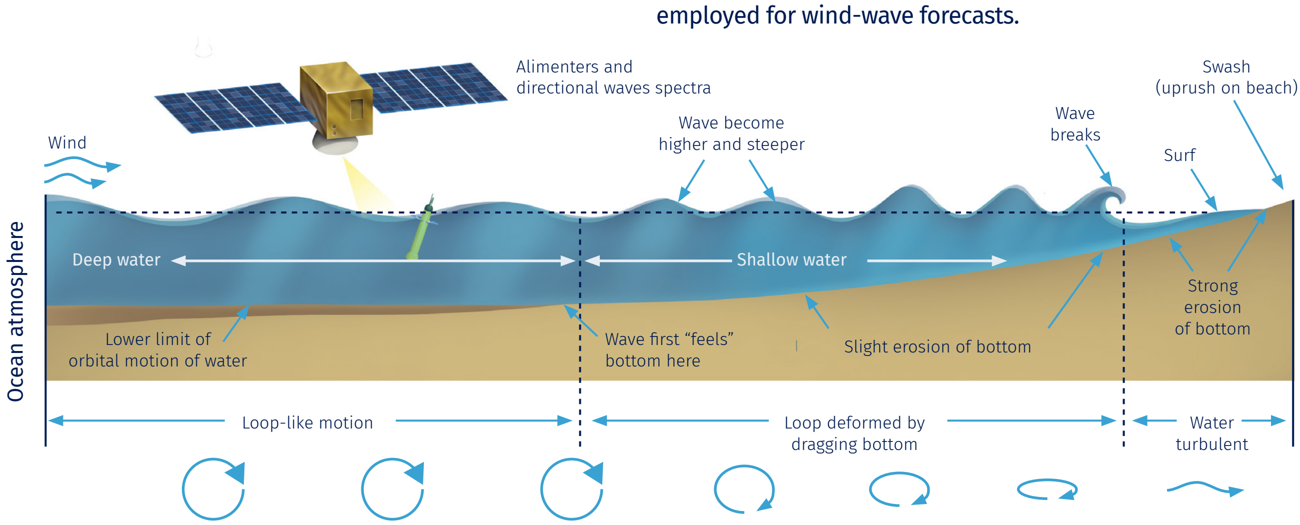
Related ocean variables

- Significant wave height
- Mean and peak period
- Mean wave direction
- Surface Stokes drift
- Wave spectra

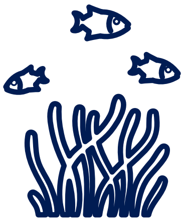
Theoretical water waves are described by their length (L), height (H), amplitude (a) or height (H), and water propagation depth (d). Other variables, such as velocities, pressures and accelerations can be explicitly mathematically calculated from the three basic quantities: amplitude (a), wavelength (L) and period (T).

Modeling ocean waves

Ocean wave modelling efforts and applications can be broadly classified into two large groups: i) phase resolving (or direct) models; and ii) phase average (usually spectral) models. Direct models can explicitly simulate basic equations of fluid mechanics for the water, air, or even two-phase media, and therefore extend the analytical research beyond its traditional range of approximate and asymptotic solutions of such equations. At oceanic scales, however, such models are not practical and not feasible, and therefore spectral models are employed for wind-wave forecasts.



Change in orbital motion of water particles



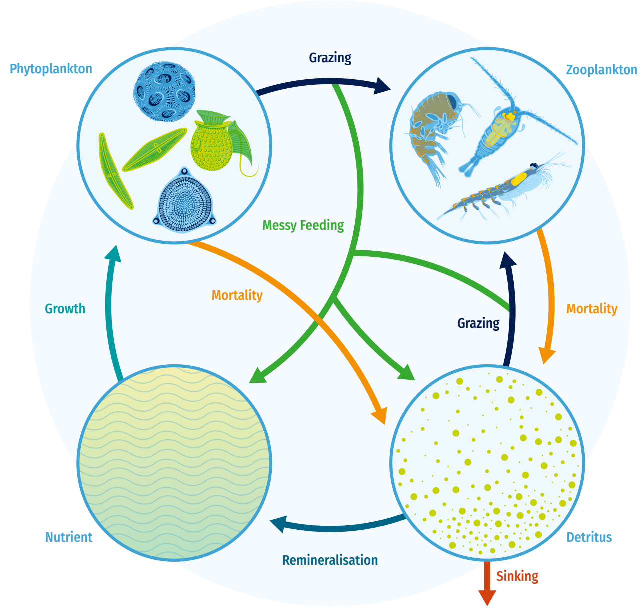
Biogeochemical modeling

Marine biogeochemistry is the study of essential chemical elements in the ocean (such as carbon, nitrogen, oxygen, and phosphorus), and of their interactions with marine organisms. Biogeochemical cycles are driven by physical transport, chemical reactions, absorption, and transformation by plankton and other organisms, which form the basis of the oceanic food web.

What is marine biogeochemistry?

Marine biogeochemistry, the study of elemental cycles and their interactions with the environment and living organisms, is a multidisciplinary science at the crossroads between ocean physics, chemistry, and biology, and intersects with atmospheric and terrestrial sciences as well as social science and environmental policy.

Ocean BGC models describe the base of the marine food chain from bacteria to mesozooplankton and couple the cycles of carbon (C), nitrogen (N), oxygen (O2), phosphorus (P) and silicon (Si). They mostly focus on plankton, classifying the plankton diversity in accordance with their functional characteristics, the so-called Plankton Functional Types (PFTs).

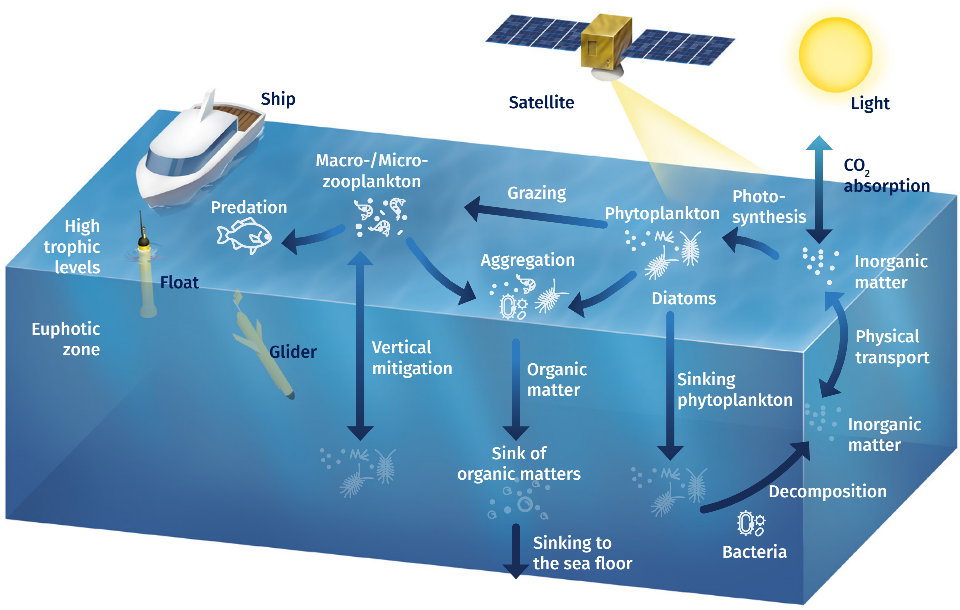


Modeling biogeochemistry

Plankton (including phytoplankton and zooplankton) are organisms which are carried by tides and currents, or do not swim well enough to move against them. They form the base of the marine ecosystem and are a central component of the BGC models that simulate the cycling of elements through seawater and plankton. Most models take an "NPZD" approach, simulating:

- Nutrients: substances which organisms require for growth.
- Phytoplankton: microscopic algae which obtain energy from sunlight through photosynthesis.
- Zooplankton: planktonic animals which obtain energy by eating other organisms.
- Detritus: dead and excreted organic matter.

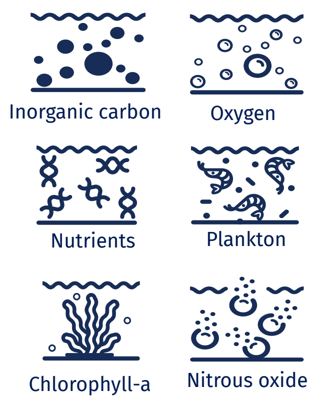
Required fields are currents, temperature, salinity, vertical diffusivity coefficient (Kz), and MLD. They are provided by a physical model to the biogeochemical model with which it is coupled in either "online" or "offline" mode. Advection and diffusion routines are usually shared with the physical model. Observations are essential for calibrating the formulation of the biogeochemical processes and for validating the model results.



Key challenges

- Biodiversity protection
- Acidification
- Eutrophication
- Harmful algae bloom

Related ocean variables



Coupled modeling

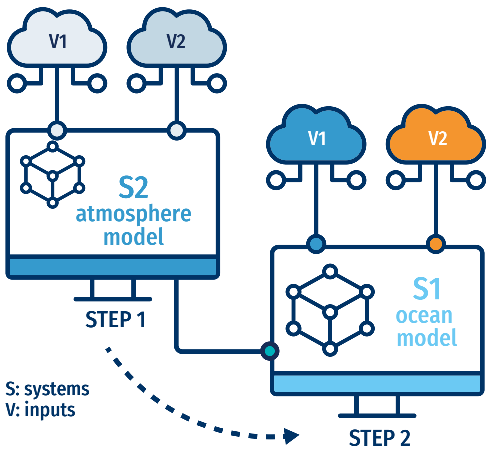
In the early days of numerical modelling of the various components of the Earth system, each component was treated individually: the output of one system is used to "force" the other. It became clear that long climate integrations of the atmosphere needed to also consider the impact of a (slowly) changing ocean, not least because the various climate components interact in nonlinear ways. This led to the first attempts at "coupling" ocean and atmosphere models. Coupler mechanisms are fundamental in ocean predictions to provide improved feedback to ocean-atmosphere-waves-land systems through advanced modelling.

What is a coupled model?

To be more accurate and take into account more variables, it is sometimes useful to implement coupled-models where two or more models are associated into a single numerical system. The advantage of coupled models is that changes in a model can directly and immediately influence the other model. There are errors in ocean-only models due to the lack of representation of ocean-atmosphere, ocean-land or ocean-sea-ice interactions. There are a number of solutions to how this coupling may be achieved, and which is optimal will depend both on the scientific importance of the exchanges and the timescales on which they occur as well as on technical limitations.

Traditional models

Models are run independently and fed with a flux of information from adjacent components of the earth system in a non-interactive way. Implication: the winds, precipitation and air temperatures ("forcing") used to drive the exchanges at the ocean's surface do not respond to changes in the ocean conditions themselves.



Next coupled model challenges for more accurate ocean forecasts

FURTHER IMPROVE THE COUPLING

- Air/Sea ice
- Hydrodynamic/Biogeochemistry

BETTER INTEGRATE

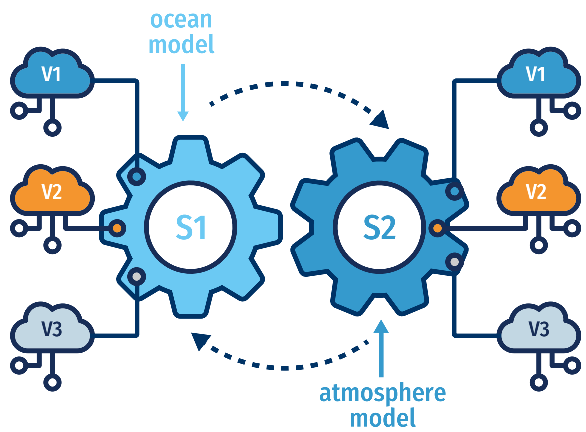
- Land/Sea
- Atmosphere/Sea

OCEAN INFORMATION SERVICES BASED ON COUPLED SYSTEMS

- Importance of air-sea exchanges during storms and extreme events
- Regional hazards prediction

Coupling models

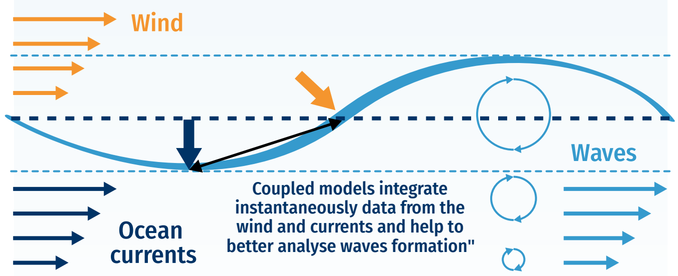
Independent models communicate with each other often through an interface code ("coupler") which allows the independent models to operate on different grids and with different time steps.



Focus on Atmosphere-Waves-Ocean circulation (AWO) coupled models

THE NEED TO USE COUPLED AWO:

- is well understood and mature for seasonal and climate prediction due to the role of the ocean-atmosphere feedbacks in the earth heat budget (climate) and in large scale weather phenomena such as ENSO (seasonal);
- is not as well developed for shorter-range prediction where the trade-off between complexity (coupled) and resolution has tended to favor resolution.



Downstream application: from products and services to outreach

One of the main characteristic of an Operational Oceanography System is its ability to provide updated data on a regular basis to its users. Data is provided to end-users to develop specific solutions to marine challenges.

Main downstream applications and their purpose for society and policies

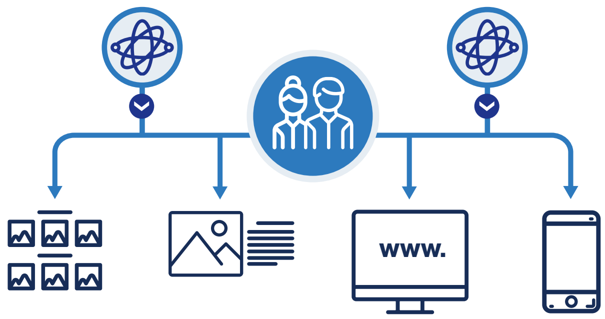
Operational oceanography is available nowadays to many users through solutions (services and products) dealing with several **Sustainable Development Goals** (SDGs), and societal and scientific challenges. Oceanographic products from global to regional scale are produced by national and international forecasting centres. They are then downscaled to sub-regional scales, transformed, and provided to users, private companies, public users, stakeholders, and citizens through an ocean products value chain.

Disseminating scientific knowledge

Operational oceanography centers provide routine products and information at pre-determined and agreed service level.

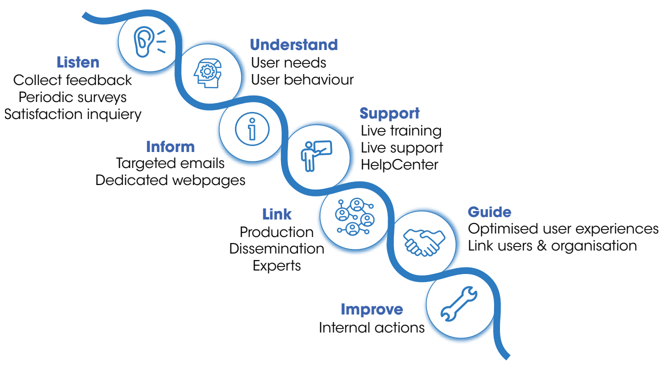
Tools are developed to allow a wide and efficient diffusion of the data such as:

- dedicated webpages,
- visualisation tools,
- an accessible data catalogue,
- an applications portfolio capable of highlighting data used to benefit society,
- a user support service with human interactions.

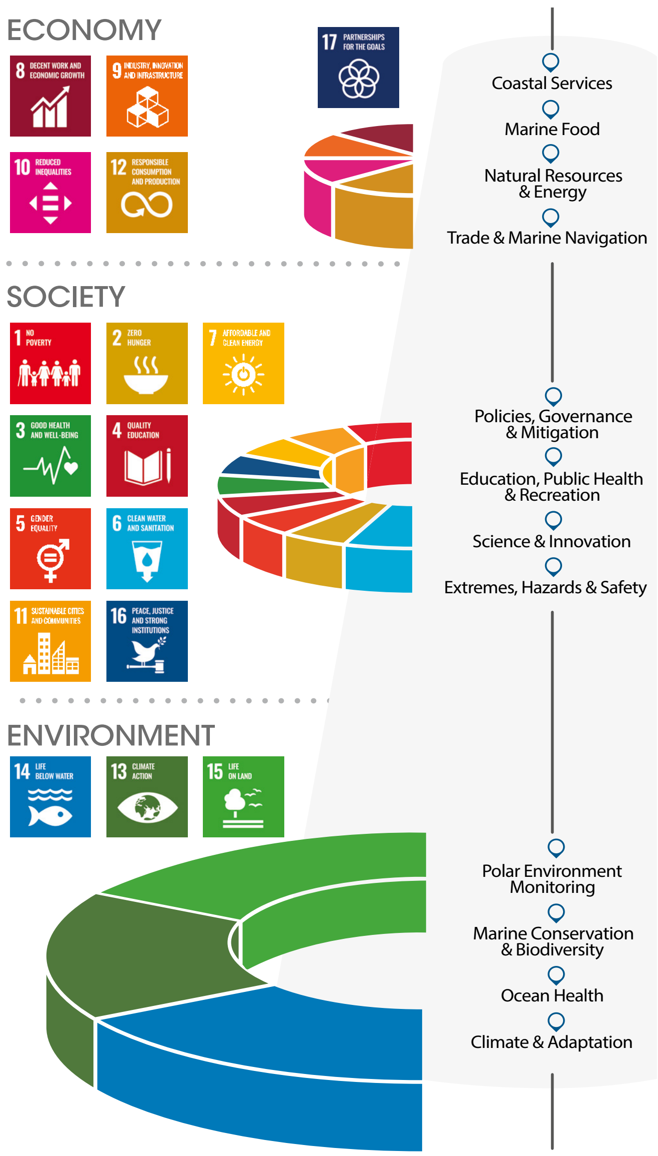


Supporting users and applications with human interaction

A user support service, along with a user learning service allows us to better understand user's needs and provide them with on-the-shelf or custom made products dedicated to specific applications.



Monitoring the ocean to achieve all United Nations sustainable development goals



OPERATIONAL OCEANOGRAPHY AND ITS APPLICATIONS through data, information, and services, across the environment, society, economy pyramid.

Modified after von Schuckmann et al., 2020, and the Stockholm Resilience Centre.

Future perspectives on ocean modeling

The growth of ocean prediction research, applicability, availability, and user uptake from an initial idea 25 years ago, while gradual, has been unrelenting. Today's capacity and maturity in ocean prediction goes beyond initial expectations and provides tangible socio-economic benefits. Over the next 10 years, ocean prediction systems will continue to gradually rival weather prediction systems in the sense of ubiquitous use, protection of lives, economic impact, and supporting custodianship of the environment.

Building a framework with standards and best practices for the full operational oceanography value chain will enable further harnessing of prediction systems in supporting a healthy ocean at the same time of a blue economic growth for all countries. This will raise awareness of the marine environment through accessibility via digital platforms, underpinning developments in ocean prediction literacy, capacity building, applications, and services.

Scientific and technical ways forward

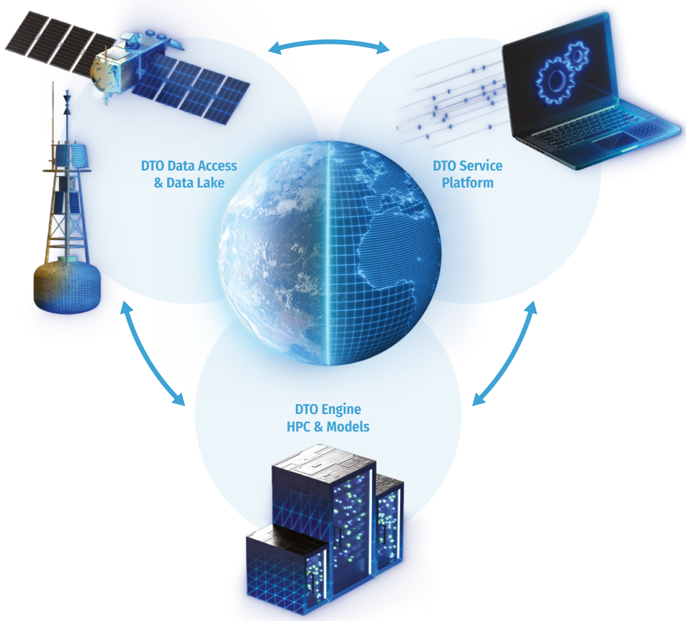
- Observing system evolution with ocean prediction engagement
- Numerical models improvements and new High Performance Computing challenges
- Evolutions in data assimilation, merging ensemble and variational methods
- Opportunities of artificial intelligence for ocean forecasting systems
- Seamless prediction
- Quality assessment for intermediate and end users

A path towards a Digital Twin Ocean (DTO)

DTO is a highly accurate model of the ocean to monitor and predict environmental change, human impact, and vulnerability, with the support of an openly accessible and interoperable dataspace that can function as a central hub for informed decision making.

The main aim is to deliver a holistic and cost-effective solution for the integration of all information sources related to seas and oceans (in situ-data and satellite information combined with IoT techniques, citizen science, state-of-the-art ocean modelling together with Artificial Intelligence and High Performance Computing resources, etc.) into a digital, consistent, high-resolution, multi-dimensional, and near real-time representation of the ocean.

This will require a multi-layered software framework where tasks like simulations, observational data ingestion, and post-processing are treated as objects that are executed on federated computing infrastructures, feeding data into virtual data repositories with standardised metadata, and from which a heavily machine-learning-based toolkit extracts information that can be manipulated in advanced ways.



Schematic representations of Digital Twin of the Ocean concept and architecture

Future perspectives on ocean modeling

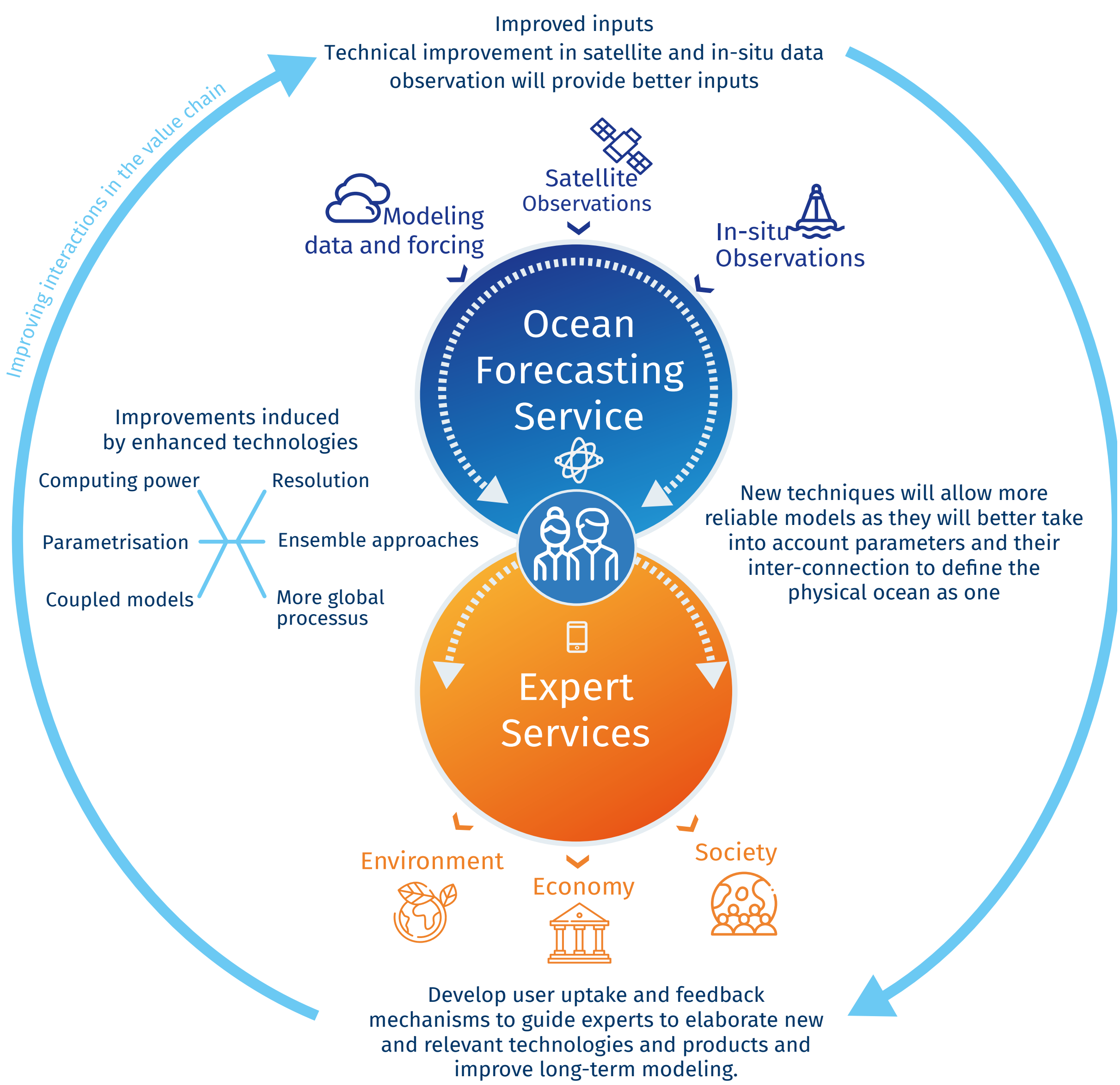
Perspectives on the Operational Oceanography and Forecasting Systems Value Chain

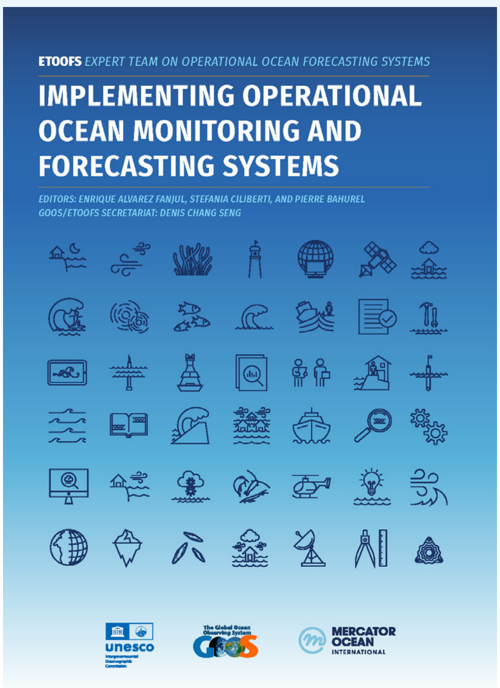
The United Nations Decade of Ocean Science for Sustainable Development has been launched in 2021 to *support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework that will ensure ocean science can fully support countries in creating improved conditions for sustainable development of the Ocean.*

The decade will be implemented via "Programmes", which are the tangible integrating initiatives that will be carried out across the globe over the next ten years to fulfil the Ocean Decade vision. The **Decade Collaborative Centre for Ocean Prediction**, coordinated by Mercator Ocean International will work with decade programmes to deliver a predicted ocean based on a shared and coordinated global effort in the framework of the UN Ocean Decade

CoastPredict programme, coordinated by University of Bologna, will focus on coastal resilience in a changing climate. The main objective is the co-design and implementation of an integrated coastal ocean observing and forecasting system, adhering to best practices and standards, designed as a global framework, and implemented locally.

ForeSea programme, to be hosted by OceanPredict (https://oceanpredict.org/) will have the objective of building the next generation of ocean predictions, pursuing a strong coordination of the scientific community and institutes at the international level, and creating a seamless ocean information value chain, from observations to end users, able to support the economy and society.





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