The Global Ocean Observing System

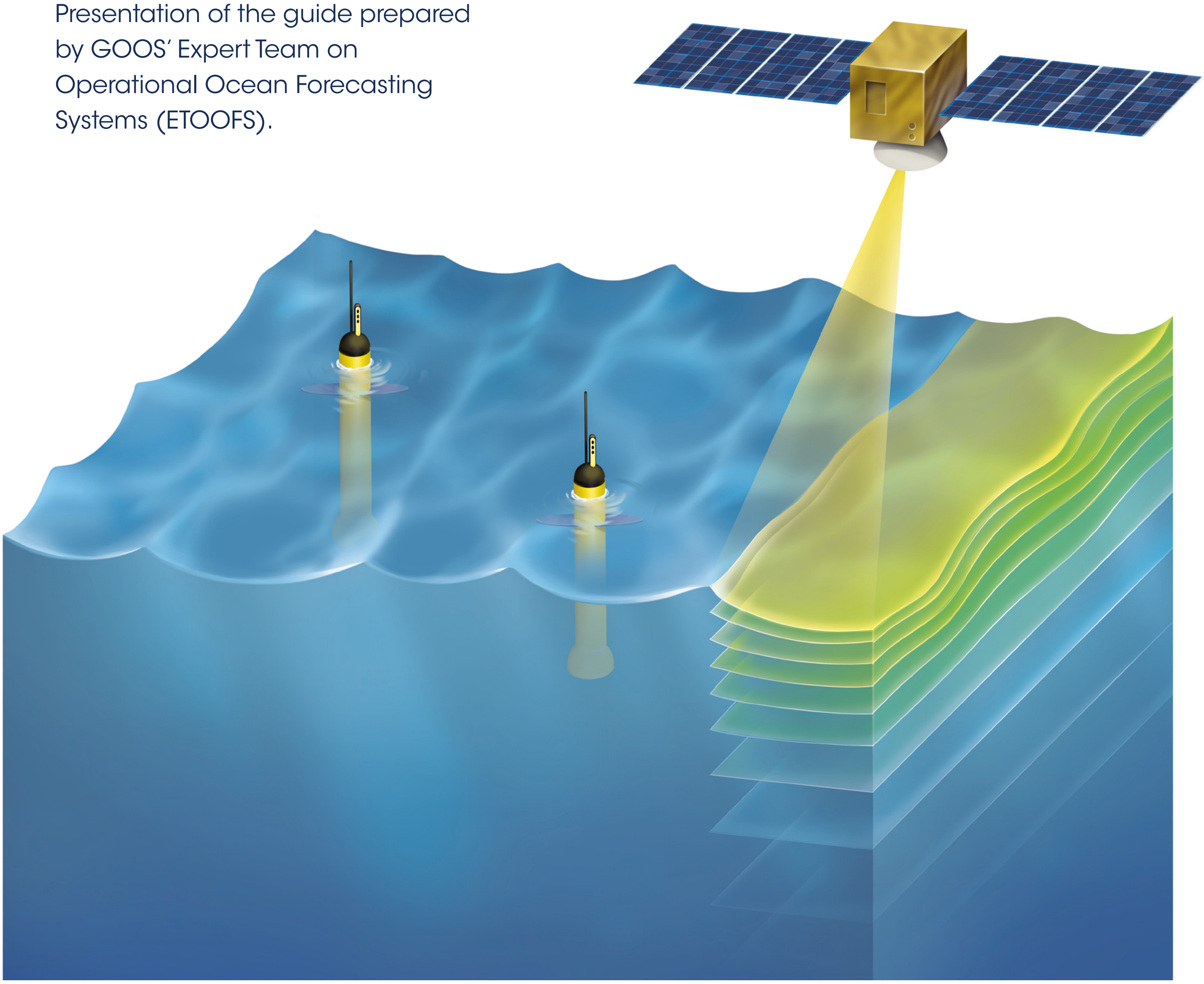
United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

WORLD METEOROLOGICAL ORGANIZATION

Implementing Operational Ocean Monitoring and Forecasting Systems

Presentation of the guide prepared by GOOS' Expert Team on Operational Ocean Forecasting Systems (ETOOFS).

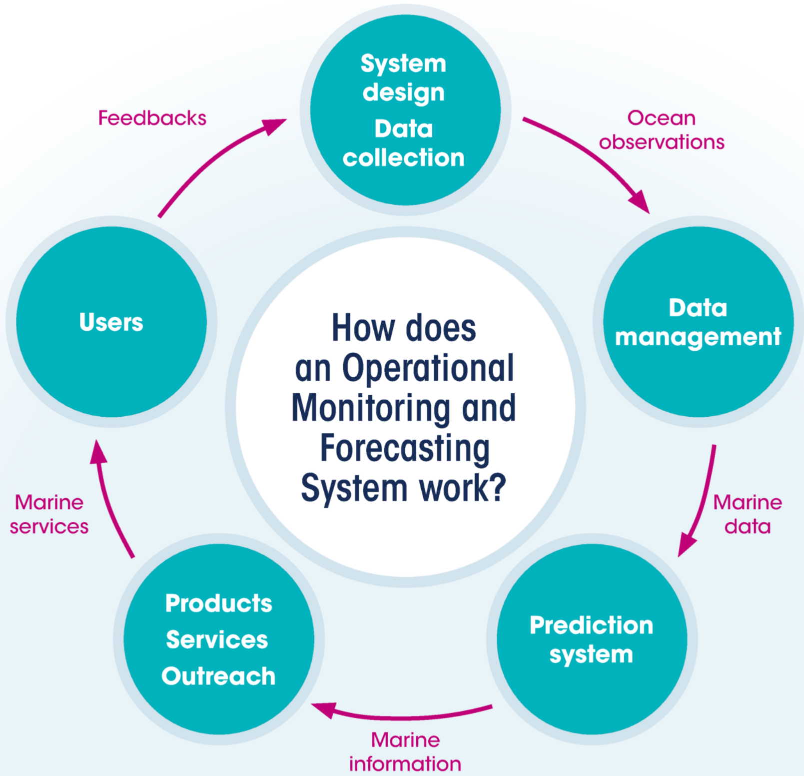


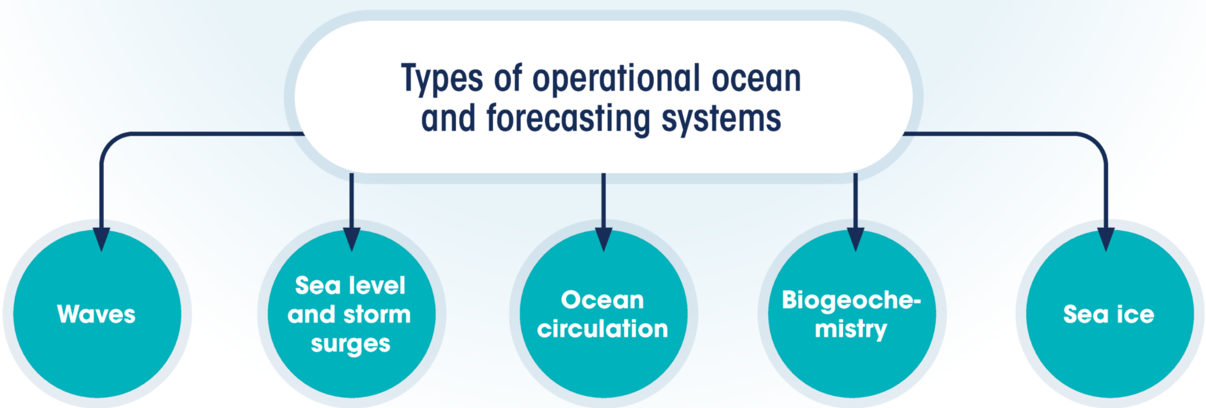
WITH THE SUPPORT OF MERCATOR OCEAN INTERNATIONAL

A Guide on 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 prepared a guide on international standards and best-practices for setting up an operational oceanography and forecasting systems service. This document is a summary of the Guide on Operational Ocean Monitoring and Forecasting Systems and presents its major characteristics in a synthesised way.

Today, every single country in the world with a coastline, or not, is likely to engage in marine activities for national security, environmental protection and maritime economic development. Such activities require the monitoring and forecasting of the physical, biogeochemical and sea ice state of the ocean on a daily basis. Operational oceanography relies on expertise and brings the relevant ocean data for monitoring an assesment. The scientific and technical knowledge assembled in the guide serves to facilitate the implementation of an efficient Operational Oceanography and Forecasting service.





Operational Oceanography

Operational oceanography can be defined as the activity of providing estimates of the Blue (physics: temperature, salinity, etc.), White (sea ice) and Green (biogeochemical: chlorophyll, dissolved oxygen, etc.) ocean variables for the past, present and future global-to-coastal marine environments. It involves Operational Ocean Monitoring and Forecasting Systems which encompass the collection of ocean observations, modeling of the current ocean state, short-range predictions and ocean reanalyses, and scientific verification. It also supplies routine products and information at agreed service levels to enable marine policy implementation, support Blue Growth and scientific innovation.

To outline the Guide, the booklet uses the same structure and summarises each one of its chapters in one page.

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Citation: Enrique Alvarez Fanjul, Lotfi Aouf, Pierre Bahurel, Giovanni Coppini, Stefania Ciliberti, Fraser Davidson, Elodie Gutknecht, Avichal Mehra, John Siddorn, Dakui Wang, Fujiang Yu.

Disclaimer: this summary has been written by Mercator Ocean International in collaboration with IOC/UNESCO, communication professionals and scientists. It is intended to provide key information and an accessible explanation of the GOOS Guide on Operational Ocean Monitoring and Forecasting Systems.

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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

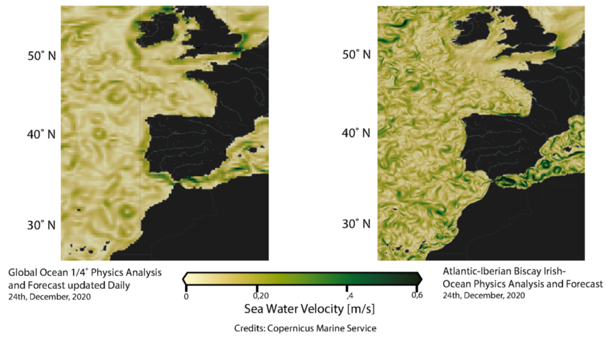
- **70%** of the Earth surface
- **50x** absorption of carbon compared to atmosphere
- **40%** of the world population concentrated on coastlines
- **15.7%** fish protein consumed worldwide
- **90%** of the world's trade

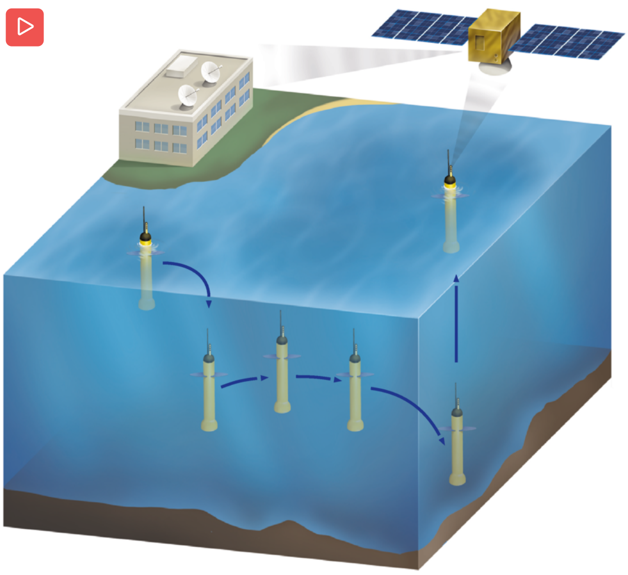
A science in constant evolution

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.

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.

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.





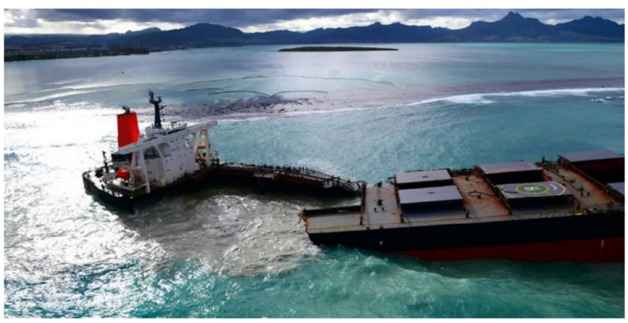
Building ocean physics model: data collection, assimilation and processes

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.

In situ buoys sample the ocean surface and depth and transfer their measurements to operational oceanography centers via satellite communication. The ocean can as well be monitored with satellites that take images of the Earth surface (see cover page).

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.



MV Wakashio oil spill in Mauritius.
Source: International Maritime Organization (IMO) flicker account

Motivation and Scope of Ocean Monitoring and Forecasting Capacity

Launched by an international impetus, ocean monitoring and forecasting includes the collection of in situ and satellite observations, numerical modeling and data assimilation. Its strength lies in the overall value brought to end-users to help them implement their marine applications.

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.

- **90's** – creation of operational oceanography
- **1991** – GOOS is created
- **1997** – GODAE Initiative
- Development of many operational oceanography centers worldwide

Societal importance of ocean monitoring and forecasting system

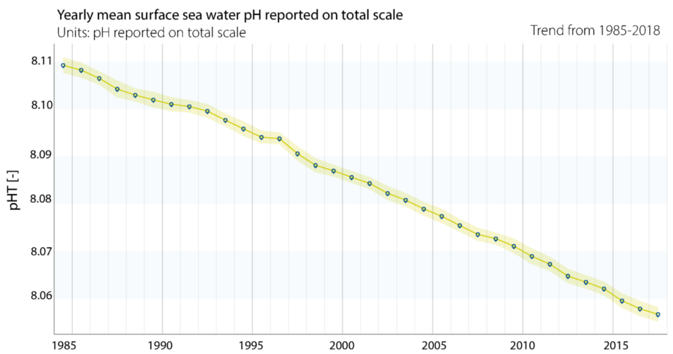
OPERATIONAL SERVICES
- Hazards: tsunamis, storm surges, high waves
- Costal services
- Navigation
- Energy

CLIMATE
- Ocean heat
- Sea level rise
- Sea ice

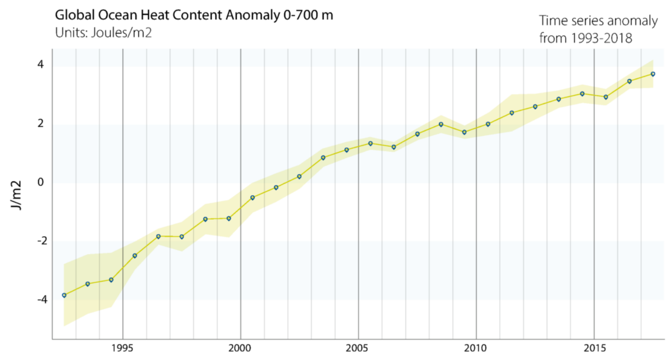
MARINE ECOSYSTEM HEALTH
- Ocean health
- Marine biodiversty conservation
- Food

Monitoring the global ocean acidification trend from 1995 to 2018 allows to understand the impacts of CO_2 emissions on the health of the marine ecosystem, such as coral bleaching.

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.



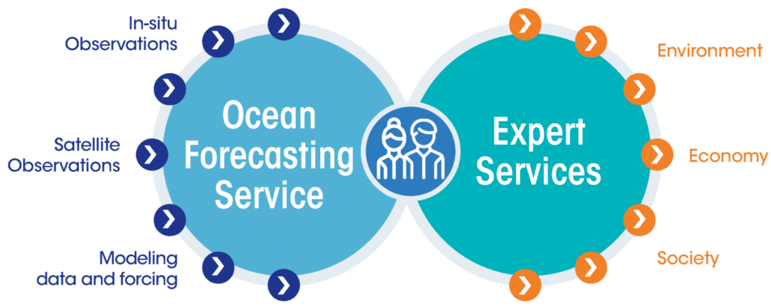
Annual global mean surface seawater pH derived from the Ocean Monitoring Indicator "Surface Ocean pH", showing an overall trend for decreasing pH and increasing acidification. Source: Copernicus Marine Ocean State Report 4.



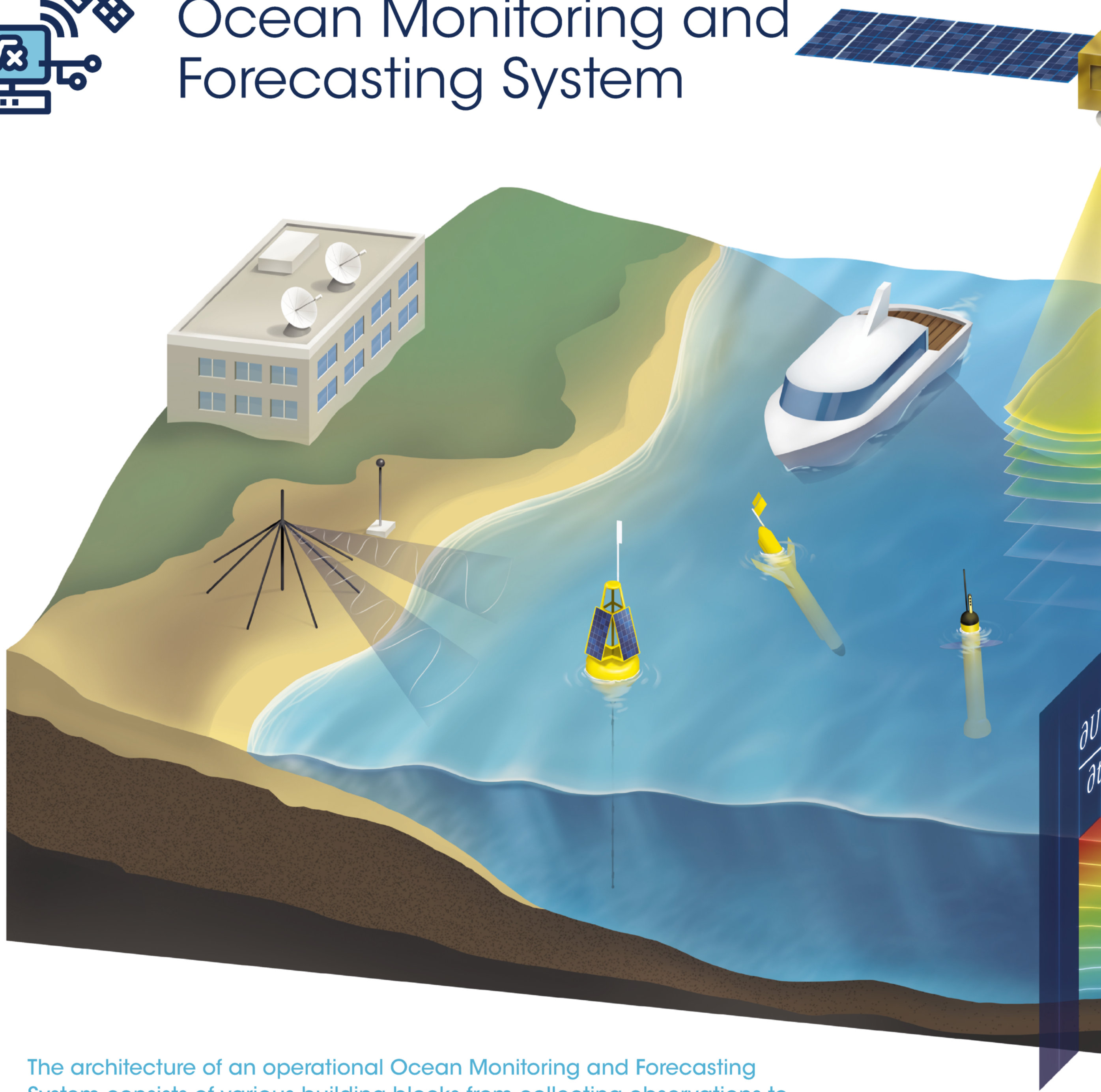
1933-2018 time series of global Ocean Heat Content anomaly in the upper 700 m of the ocean. Units are joules per square metre. Source: Copernicus Marine Ocean Monitoring Indicator.

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.



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.

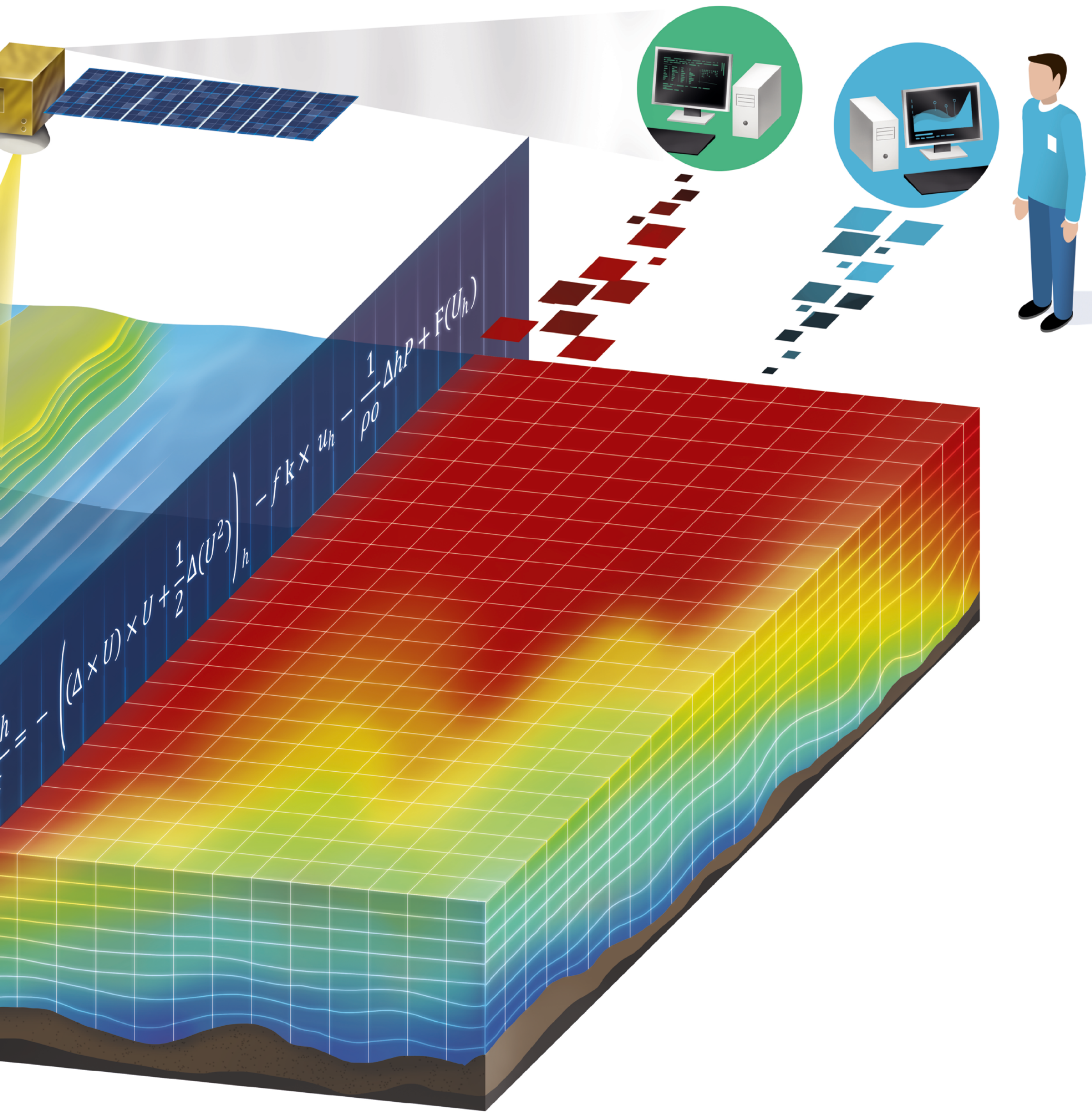
They are acquired thanks to different observation systems: satellites, buoys, ocean research vessels and underwater gliders to name a few.

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

Forward integration and post-processing

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.

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

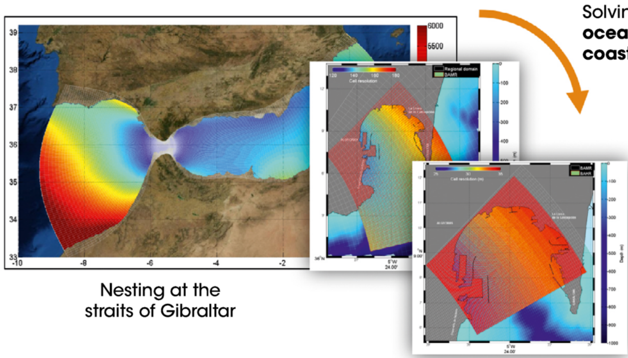
Operational Oceanography processes are described by a wide range of time and spatial scales. For example, the deep ocean and coastal ecosystems are interconnected. This means that, to represent the processes from one of them, you also need to consider the other. In order to describe the oceanic processes 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.

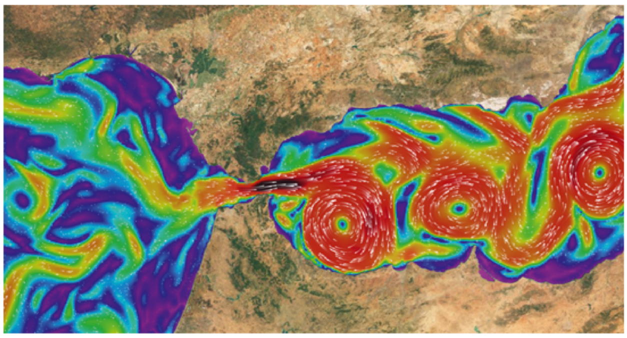


Nesting at the straits of Gibraltar

Range of temporal scales

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

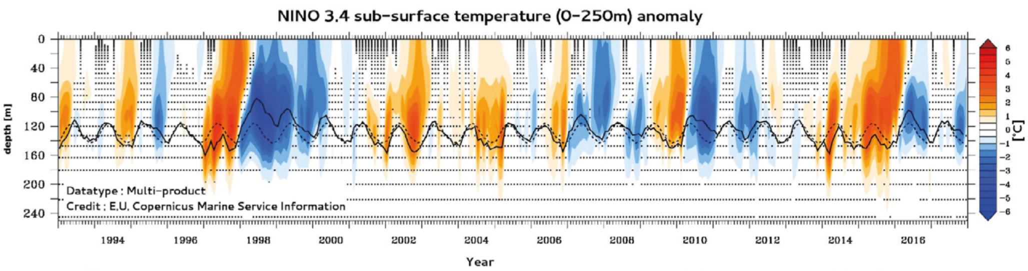
Short-range data provides knowledge of the essential ocean variables **in real time** or in **the near future**.



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

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.



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

The physical processes, properties and circulation of our ocean are described with the numerical result of the approximated Navier-Stokes equations. The state of the ocean at any time and location can be represented by three-dimensional distribution of temperature, salinity, currents, pressure, density and sea ice.

What is an ocean circulation model?

Ocean circulation modeling is one of the main block of the operational ocean monitoring and forecasting systems. It provides an overall description of the ocean's physical essential variables (i.e. temperature, salinity, currents, sea surface height, ocean heat flux) for ocean predictions and for supporting climate studies.

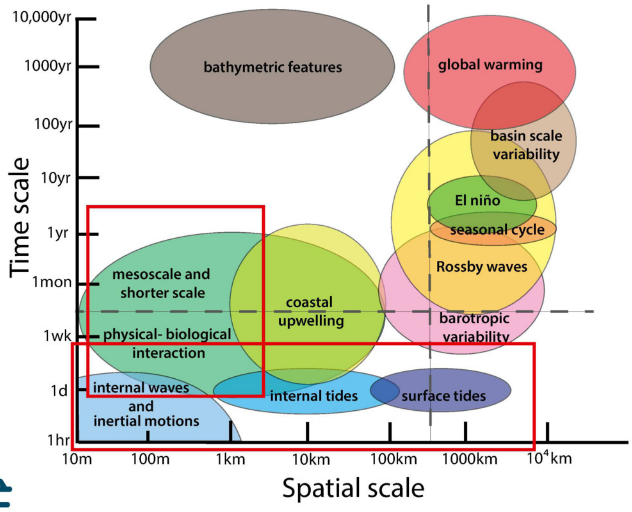
Key challenges

- Sea level rise
- Sea ice melting
- Ocean temperature trend and anomaly
- Currents for navigation, offshore energy development
- Water quality and oil spill monitoring

Related ocean variables

Various ocean circulation models

Various ocean circulation models depending on the process, spatial and time scales.



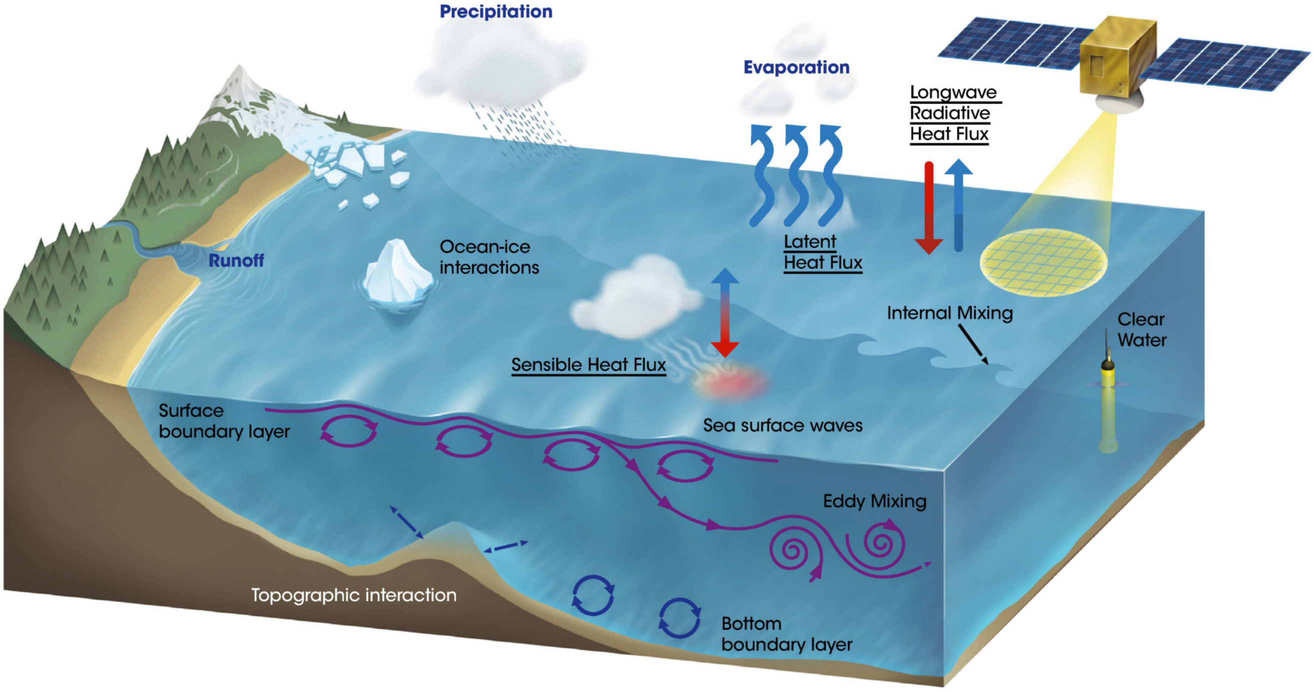
Source: modified from Dickey, 1991.

LEGEND : Main processes modeled by ocean culrculation models

Modeling ocean circulation

An ocean circulation model represents many physical processes:

- Evaporation, precipitation and runoff change the water density and salinity
- Ocean heat regulates Earth's climate system
- Currents, together with waves and tides, drive ocean mixing and water masses transformation



Sea level and storm surge modeling

The surface of the ocean fluctuates over time with periods ranging from hours to decades. It witnesses several phenomena, primarily including tides, storm surges and sea level rise caused by climate change.

What are sea level and storm surges?

Water level modeling aims at representing the evolution of the sea level, including tides, storm surge and sea level rise caused by climate change. Water level can change because of specific meteorological factors such as high-speed wind or also because of water thermal expansion: Water expands when heated and about 30% of contemporary sea level rise can be attributed to this thermal expansion (i.e. thermosteric sea level).

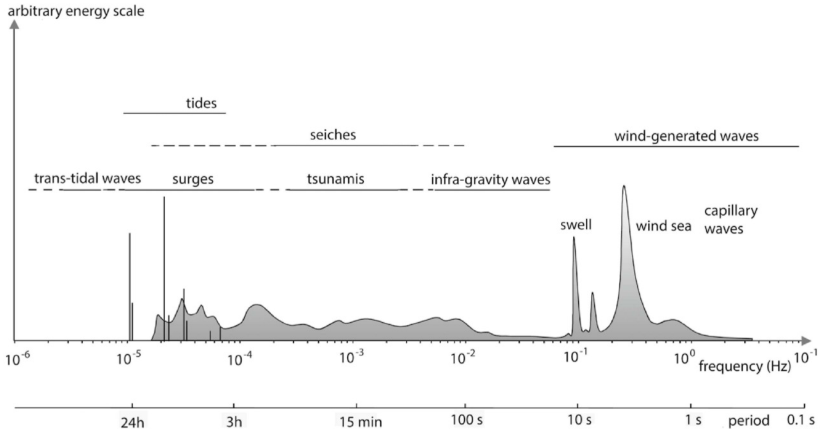
Key challenges

- Sea level rise
- Ocean flooding
- Storm surge
- Ocean disaster prevention

Related ocean variables

Sea level and storm surges processes depending on the time and energy scale

Munk W. H., 1950 — Origin and generation of waves, Proc. 1st Conf. Coastal Engineering (Long Beach), New York, ASCE



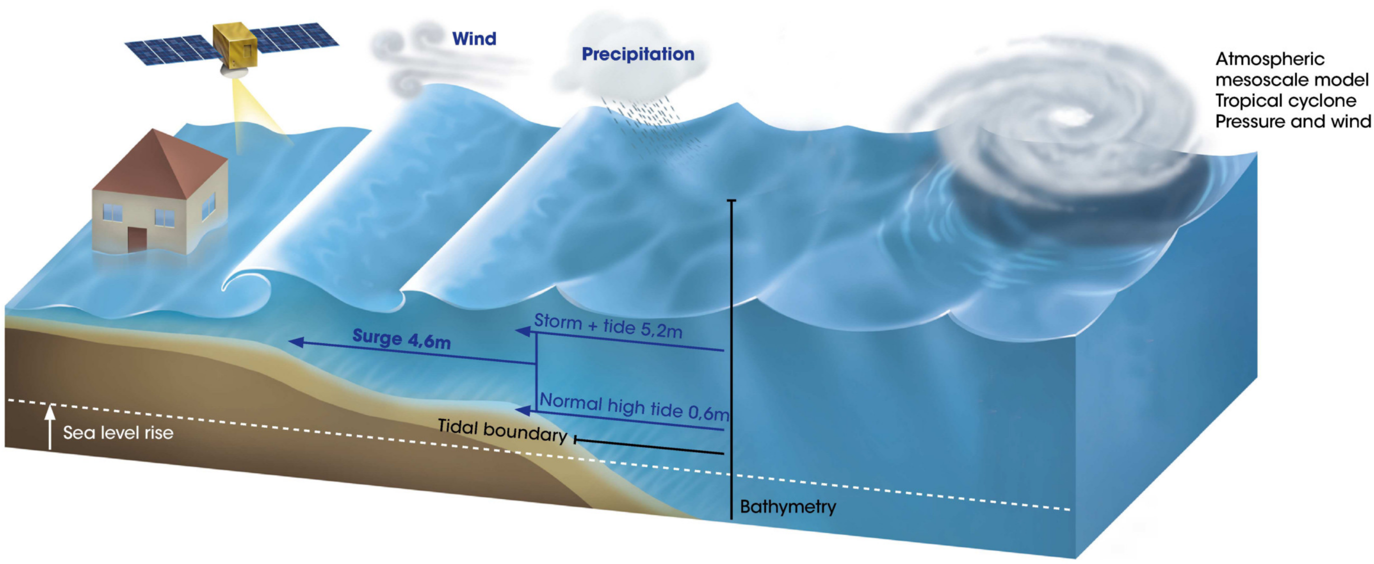
Frequencies and periods of the vertical motions of the ocean surface (after Munk, 1950)

Modeling sea level and storm surges

Water level models, whether they are tides, storm surge or climate sea level rise models each have their own characteristics in terms of physical process, grid creation, input and output data. For tide or storm surge modeling, the quality and processing of the input data are very important.

The inputs are for example:

- bathymetry: the ocean floor relief is influencing long waves propagation ➜ provide the model computing grid;
- tidal boundaries: mark on the land representing a boundary with the sea, a tidal river or a stream ➜ indicates the total water level;
- meteorological forcing including atmospheric pressure and winds resulting in huge surges during tropical cyclones.



Wave modeling

Waves processes stand between the ocean and the atmosphere and requires the most precise description of momentum and energy flows in the atmospheric and oceanic boundary layers. Implementing wave models can support many sectors of activities from maritime navigation to coastal area protection.

What does wave modeling measure?

The random nature of sea surface waves makes it one of the most complicated phenomena to represent. The numerical wave models express the physical concepts of the wave phenomena: they are based on **energy balanced equations** taking into account frequency, propagation, direction of waves and are defined for a given geographical area and time.

Key challenges

- Coastal erosion
- Navigation
- Operation at sea

Related ocean variables

Significant wave height

Modeling ocean waves

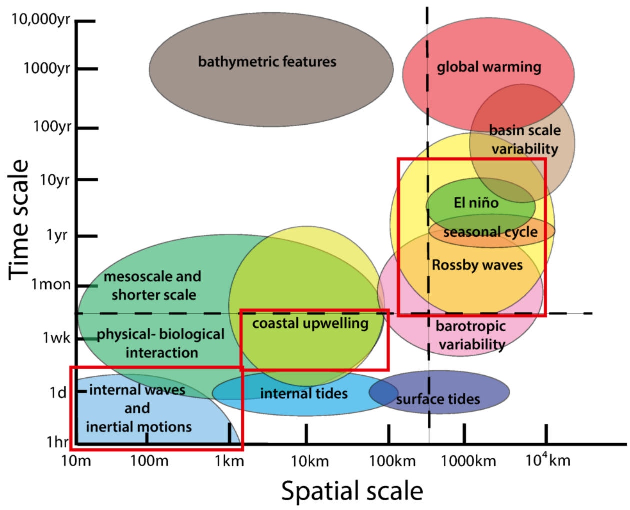
Ocean waves are the interface between the atmosphere and the ocean. Thus, their monitoring is of prime importance.

Many steps have to be performed to properly monitor waves:

- Collect wave observations (wave height and energy) from altimeters and in situ sensors
- Match wave propagation schemes with the right projection grid (regular, irregular and multiple)
- Carefully choose data assimilation techniques: it reduces model errors
- Perform scientific validation: the robustness of the wave system is directly linked to strategies and metrics used for validation

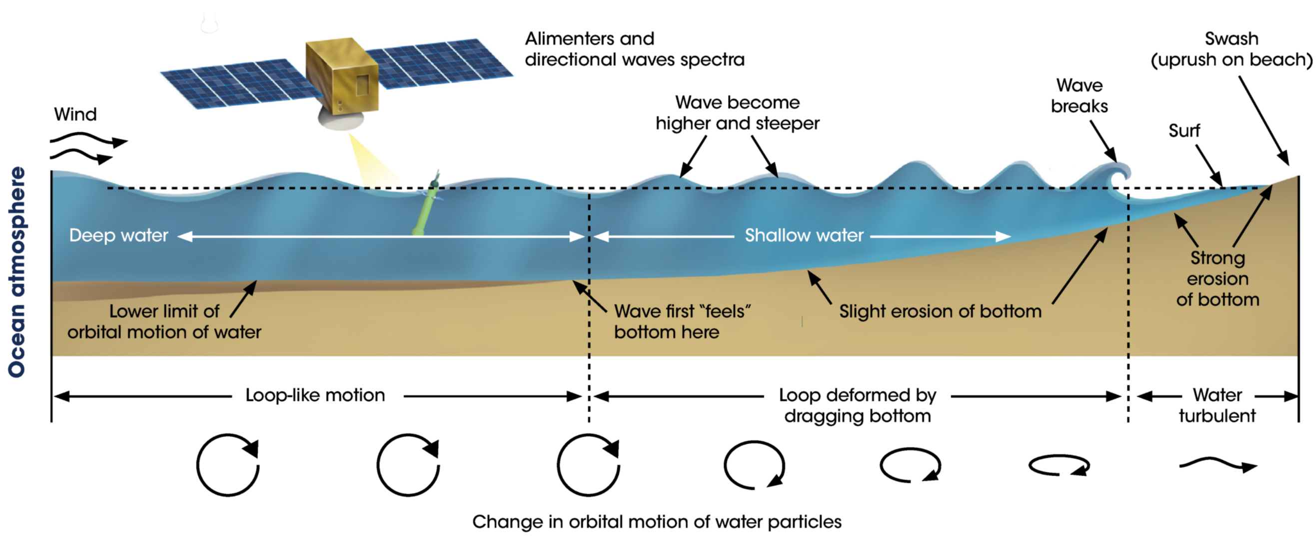
Various wave models

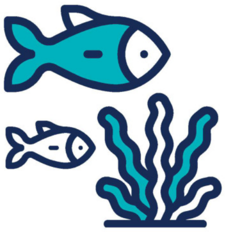
Various wave models depending on the process, spatial and time scales.



Source: modified from Dickey, 1991.

LEGEND : Main processes modeled by wave models





Biogeochemical modeling

The ever-increasing pressure of human activities have led to significant changes in marine ecosystems, closely linked to the alteration of marine biogeochemical cycles. Marine biogeochemical modeling enables us to understand the basis of the marine food chain and represents the link between the physics of the oceans and the higher trophic levels of marine ecosystems.

What is marine biogeochemistry?

Marine biogeochemistry studies the cycles of chemical elements, their interactions with the environment and their incorporation into living organisms. It is a multidisciplinary science at the interface between ocean physics and chemical transformations, the marine food chain, atmospheric conditions, continental inputs, sediments, climate change, etc.

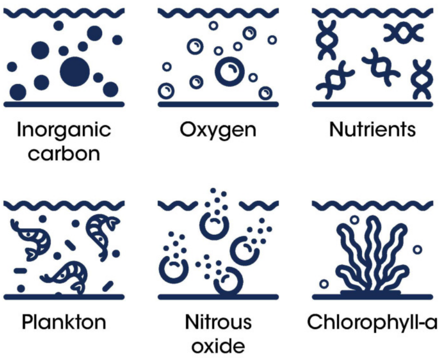
Key challenges

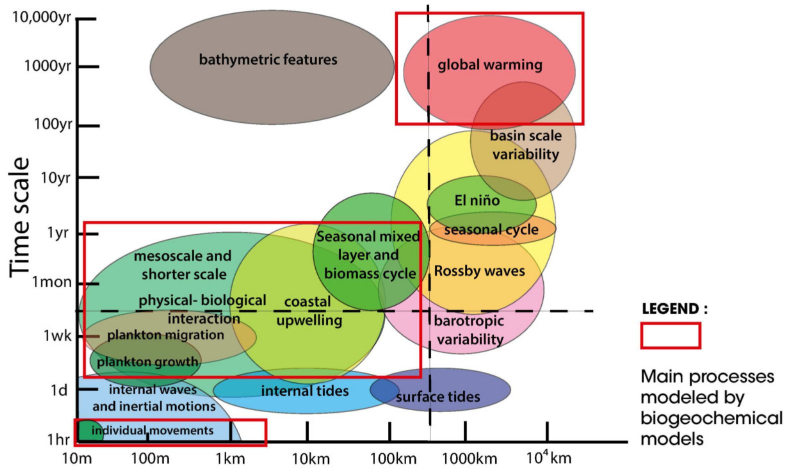
- Biodiversity protection
- Acidification
- Eutrophication
- Harmful algae bloom

Various biogeochemical models

Various biogeochemical models depending on the process, spatial and time scales.
Contrary to ocean circulation models that describe the fluid dynamics equations, there are no fundamental laws to describe the food-web dynamics. Therefore, multiple biogeochemical/ecosystem models exist, depending on the theme of interest, the complexity in biodiversity, etc.

Related ocean variables

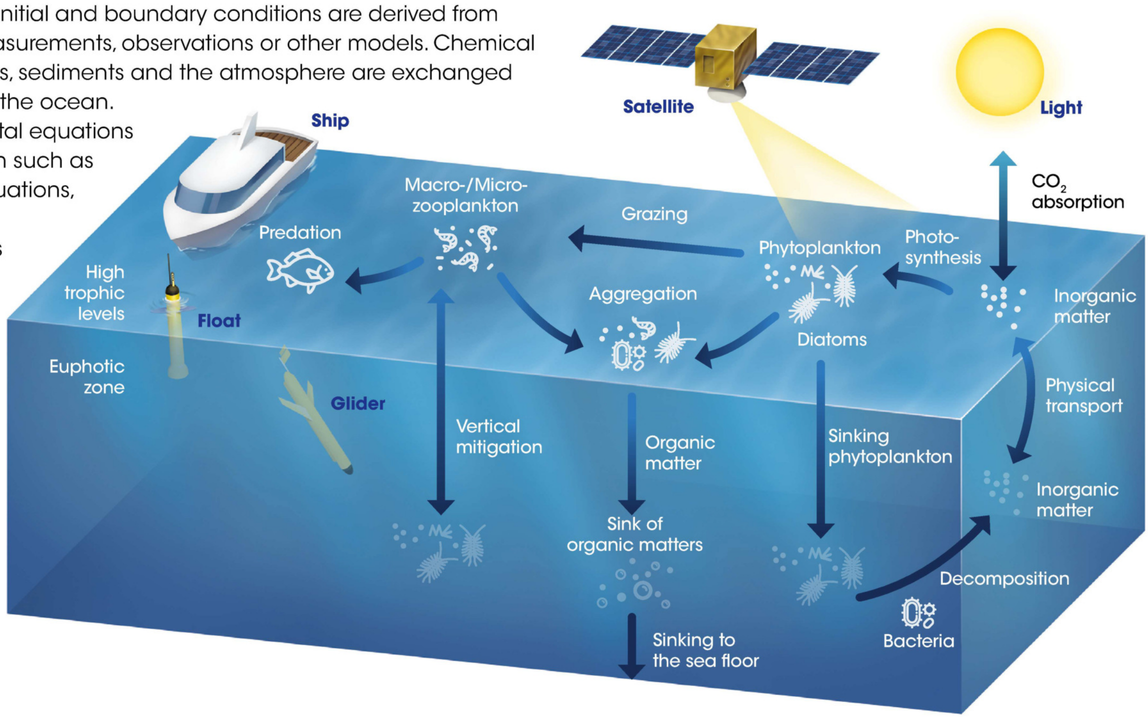




Source: modified from Dickey, 1991.

Modeling biogeochemistry

A biogeochemical model is driven by an ocean circulation model: it runs simultaneously with or is forced by the outputs of a ocean circulation model. Initial and boundary conditions are derived from climatological measurements, observations or other models. Chemical elements from rivers, sediments and the atmosphere are exchanged with or supplied to the ocean.
Without fundamental equations to drive its evolution such as fluid mechanic equations, biogeochemical modeling depends primarily on observational data to challenge model formulations.



Coupled modeling

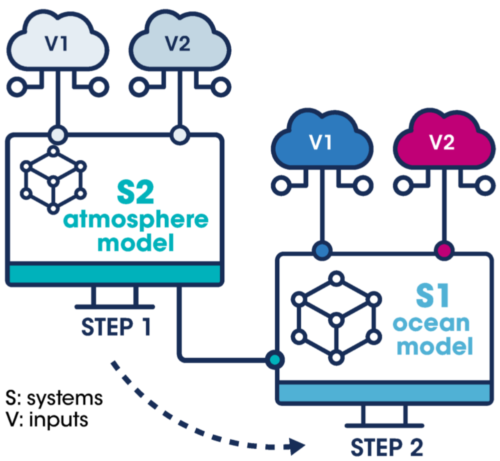
To better represent the ocean, information needs to be exchanged between the various modes: models are then coupled. If it is common to couple for example ocean circulation and biogeochemistry models, many adjacent components can be added to the traditional models.

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.

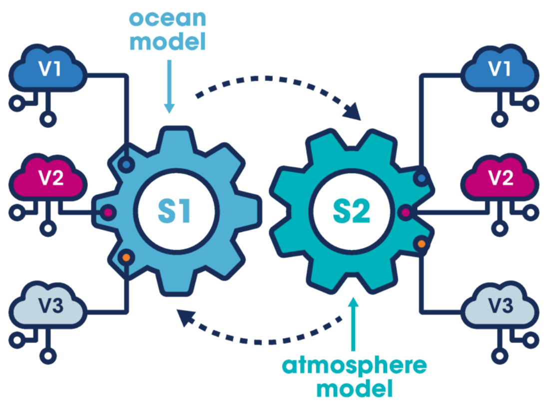
Traditional models

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.



Coupling models

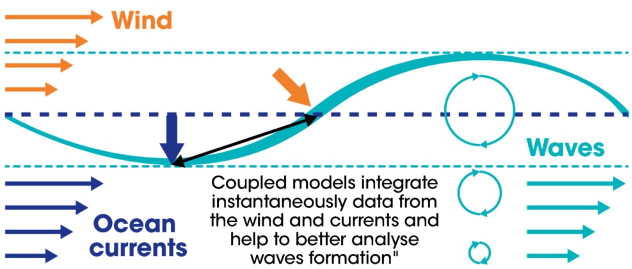
Independent models **communicate with each other** often through an interface code ("coupler") which allows the independent models to operate on different grids and with different time steps.



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.



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

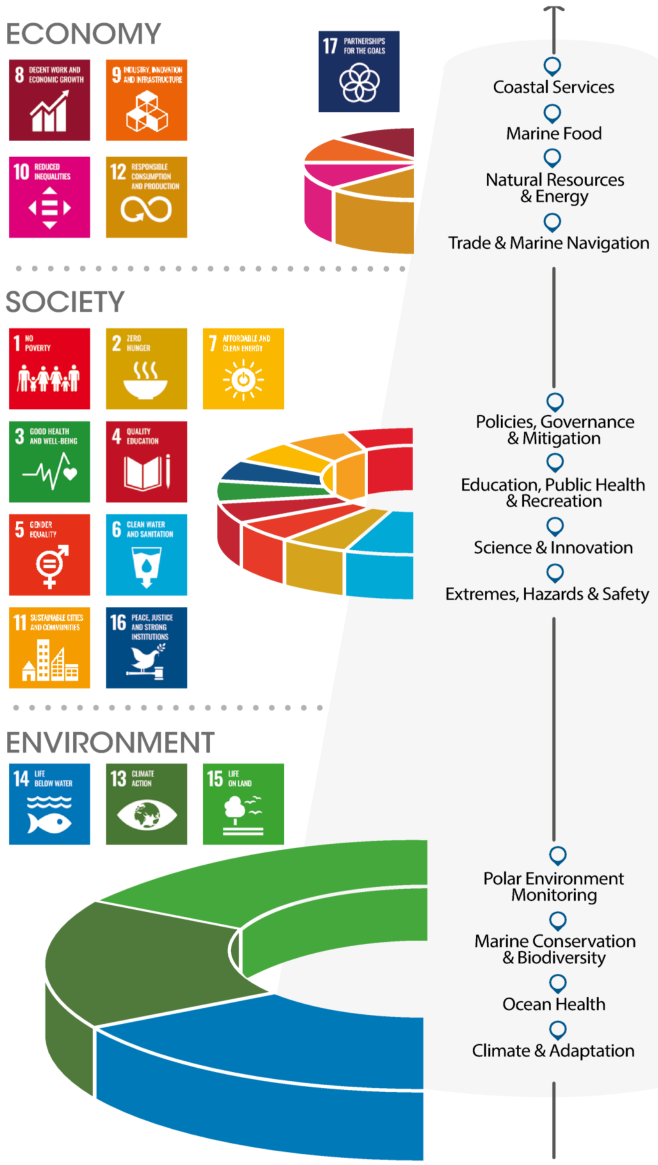
Downstream application: from products and services to outreach

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

At the end of the ocean value chain, the Operational Oceanography center transfers its ocean products to the appropriate users and beneficiaries in the formats and medias most useful to their operations. Users then develop downstream applications that put the ocean products to use through the development of specific solutions, advanced visualization, usage of multi-channel technological platforms, specific models, and algorithms. Downstream applications are an essential component to enable marine policy implementation, support Blue Growth and scientific innovation.

Monitoring the ocean to achieve all United Nations sustainable development goals



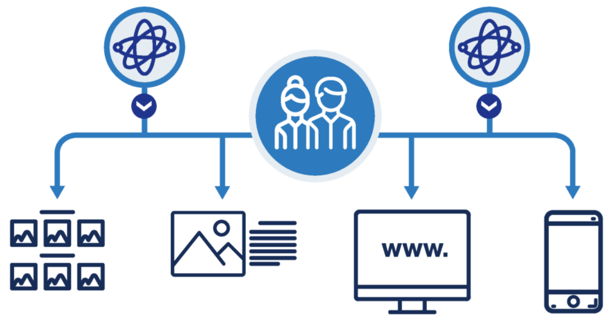
OPERATIONAL OCEANOGRAPHY AND ITS APPLICATIONS
through data, information, and services, across the environment, society, economy pyramid.
Modified after von Schuckmann et al., 2020, and the Stockholm Resilience Centre.

Disseminating scientific knowledge

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

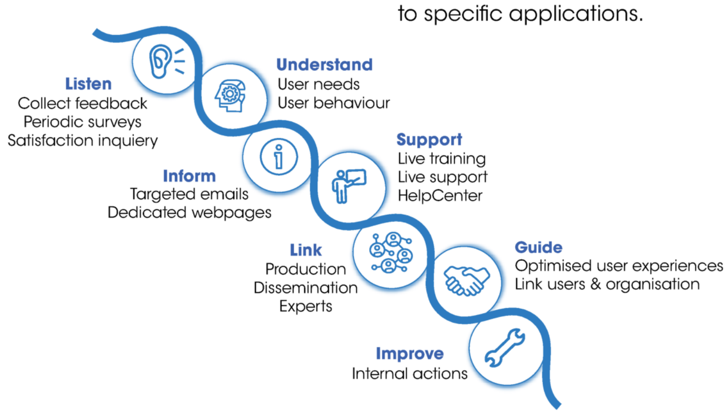
Tools are developed to allow a wide and efficient diffusion of the data such as:

- 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.



Future perspectives on ocean modeling

Ocean Observing and Forecasting Systems keep improving with new advanced methodologies applied to ocean modeling, data assimilation, collection of ocean observations as well as their implementation into operations.

Identifying user requirements to improve data relevance and long-run service quality

Important steps have been carried out to facilitate the dialogue among service providers and users:

- Identifying user requirements and needs,
- Co-developing and testing the applications and solutions.

Operational oceanography and forecast services shall:

- Gather user requirement and feedback
- Boost user uptake
- Implement service evolution strategy

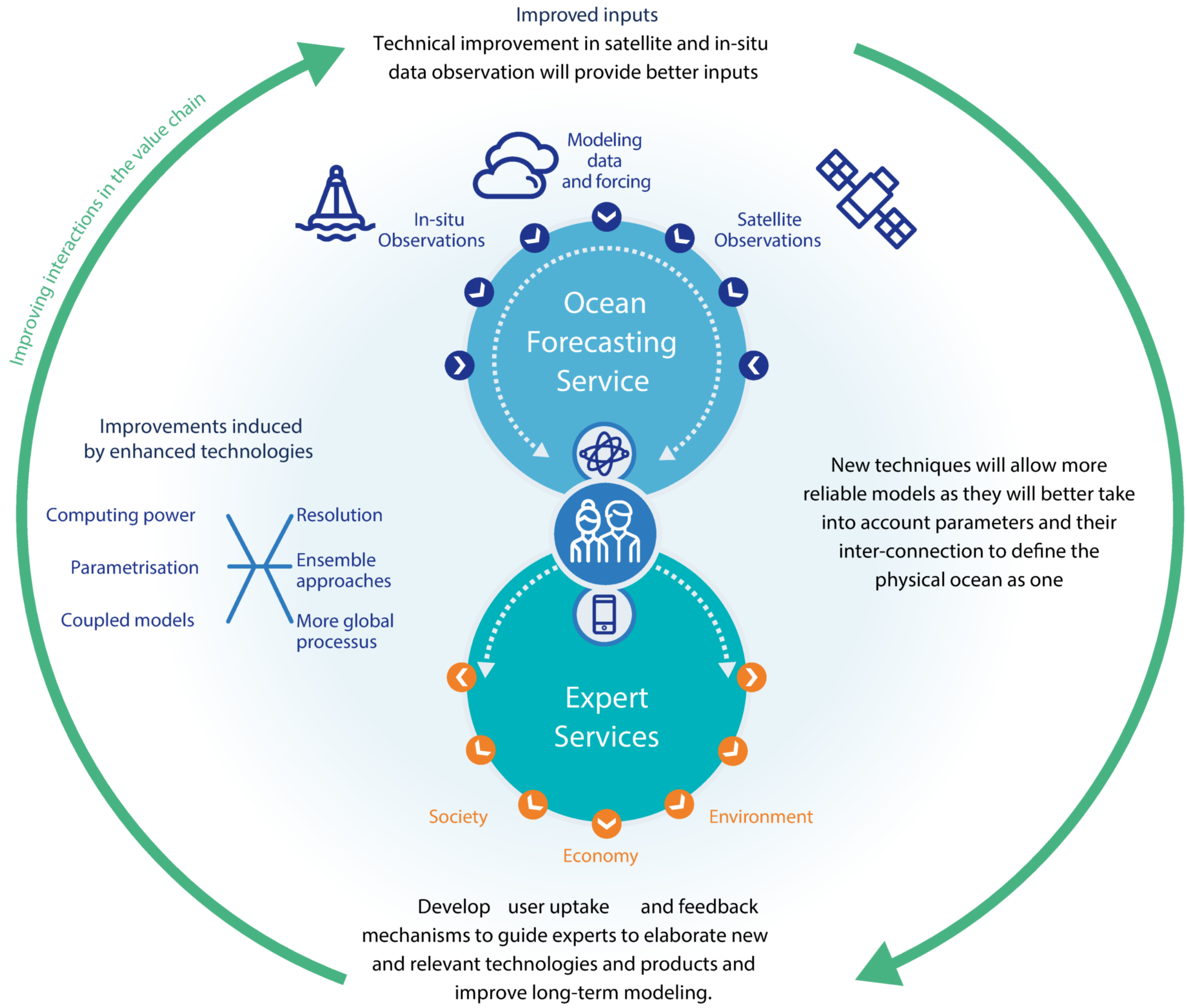
Technical ways forward

- New high-power computing systems
- Improved data assimilation
- Forecasting based on machine learning
- Seamless prediction
- Big data
- Increased resolution and accuracy of satellite observations

Focus on: a path to a digital ocean

Moving towards a **consistent, high-resolution, multi-dimensional** and **near real-time** representation of the ocean with state-of-the-art **Artificial Intelligence** and computer resources will empower scientists, citizens, governments to monitor, preserve, and enhance marine and coastal habitats.

Perspectives on the Operational Oceanography and Forecasting Systems Value Chain



About the guide on operational ocean monitoring and forecasting systems

The Guide on Operational Ocean Monitoring and Forecasting Systems will be released in 2021 jointly by the Intergovernmental Oceanographic Commission of the UNESCO (IOC-UNESCO) and the World Meteorological Organization (WMO) through the Global Ocean Observing Systems (GOOS). GOOS aims to coordinate integrated observations around the global ocean that deliver the essential information needed for our sustainable development, safety, wellbeing and prosperity. The objective of this guide is to promote the development of new marine and ocean forecasting systems around the globe, and to improve existing ones, providing valuable information to the professionals in charge of developing these services.

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WMO: wmo.int

Global Ocean Observing Systems: goosocean.org

Mercator Ocean international: www.mercator-ocean.fr

United Nations Educational, Scientific and Cultural Organization
Intergovernmental Oceanographic Commission
WORLD METEOROLOGICAL ORGANIZATION
The Global Ocean Observing System
MERCATOR OCEAN INTERNATIONAL
Copernicus Marine Service