Regional Ocean Forecasting Systems

Emanuela Clementi
Senior Scientist
CMCC – Euro Mediterranean Center on Climate Change

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Centro Euro-Mediterraneo sui Cambiamenti Climatici

Webinar of the course:
"Sustainable Coastal Growth and Resilience (Co-Growth)"
@ Coastal Resilience School

UN Decade Collaborative Centre for COASTAL RESILIENCE

www.cmcc.it

Overview

- Introduction
- Ocean prediction
- Ocean Observing Systems
- Numerical Ocean Models
- The Copernicus Marine Service
- The Mediterranean Forecasting System
- Applications

INTRODUCTION

BEGINNING 1800

Until the first decades of 1800 **oceanography** was governed by a **naturalistic approach** mainly:

- Exploration of unknown regions
- Collections of basic scientific observations

1822-1848

The **dynamic equations** were written by **Navier (1822) and Stokes (1848)** but nobody attempted to solve them as a time-dependent problem before the 20th century

$$\frac{\partial x}{\partial t} = F(x,t) + \Lambda(x,t)$$

1904, 1914

Bjerknes (1904, 1914) defined a practical way to solve these equations, coining the name ***"weather* and *hydrology predictions"*** solving N-S eq. at least for a finite and short amount of time.

1942

This descriptive approach continued until the **publication of "The Oceans" by Sverdrup, Johnson, and Fleming in 1942**
→ 1°work connecting theory and experimental data in a synthesis of ocean thermo-dynamics, dynamics, chemistry, biology and geology

INTRODUCTION

"Predictions" are the result of solving the **time evolution** of the system when both the **initial conditions** and the **boundary conditions** in the three-dimensional (3D) space are known.
This process is known as ***"integration"***

01 **Wind waves ocean forecasts 1st developed**
Sverdrup and Munk 1947 described the theory and the practical methodology for surface wind wave forecasting

02 **Sea level 2nd to be forecasted**
using only astronomical tidal forcing, winds, and atmospheric pressure

03 **1983 1st successful forecast of 3D ocean currents**
Robinson et al. 1984: two-week ocean "weather" predictions produced for the California ocean current system

INTRODUCTION

3 **Pillars** of ocean prediction science

Multidisciplinary Multi-platform Observing system
Permanent & relocatable

Numerical models
of hydrodynamics and ecosystem, coupled or forced with atmospheric forecast

Data assimilation
for optimal field estimates
& uncertainty estimates

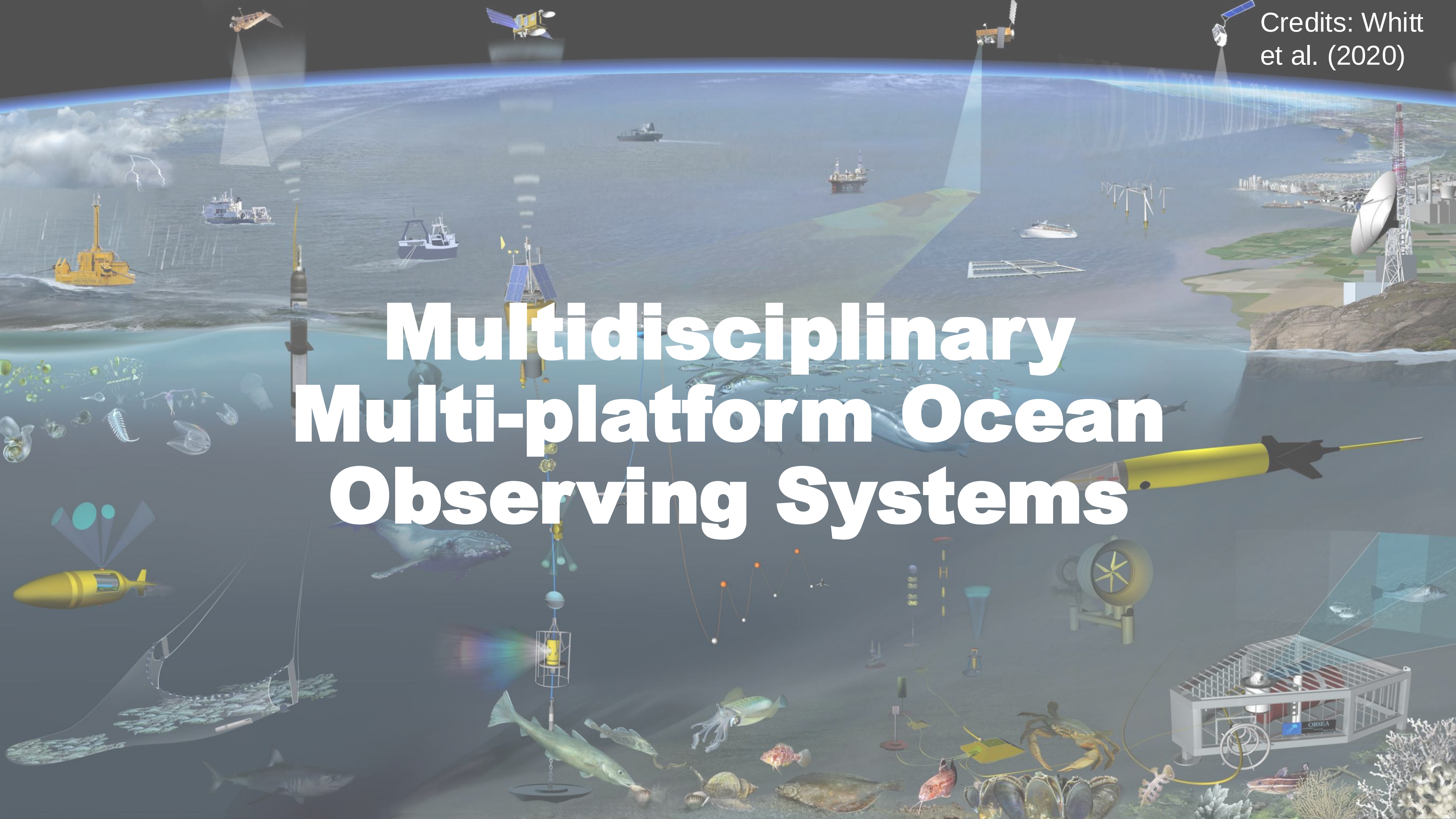
Operational Oceanography is the provision of **scientifically based** information and forecasts of the state of the sea on a **routine basis**, with **sufficient speed** to be useful to the users to take decisions in time and before the relevant conditions have changed significantly

Operational Oceanography

Continuous production of nowcasts/forecasts of relevant environmental state variables

The incremental approach:
from large to coastal space scales (NESTING), weekly to monthly time scales

Multidisciplinary Multi-platform Ocean Observing Systems



Credits: Whitt et al. (2020)

Observing Systems

- **Broad range of oceanographic observational data types**
- **Oceanographic data are collected using both remote sensing and *in situ* methods**

Some of the primary **remote sensing instruments** and resulting oceanographic data are:

- high precision **altimeters** that measure ocean surface deformation used to estimate sea surface slopes and ocean currents
- infrared **radiometers** which estimate Sea Surface Temperatures (SSTs)
- visible **radiometers** measuring ocean colour (→ Chlorophyll)
- **scatterometers** which measure wave disturbances and yield surface wind speeds and directions
- **Synthetic Aperture Radar** (SAR) estimating ocean surface currents

→ Satellite data are a major asset for oceanographic research

Long-term, continuous, global, high space & time resolution

In situ sampling measuring mainly temperature, salinity, sea level and currents such as:
tide gauges, **in situ profilers** (ARGO), **gliders**, **fixed mooring stations**, **drifters**, **ships**

Measure the water column, but limited spatial and temporal data resolution

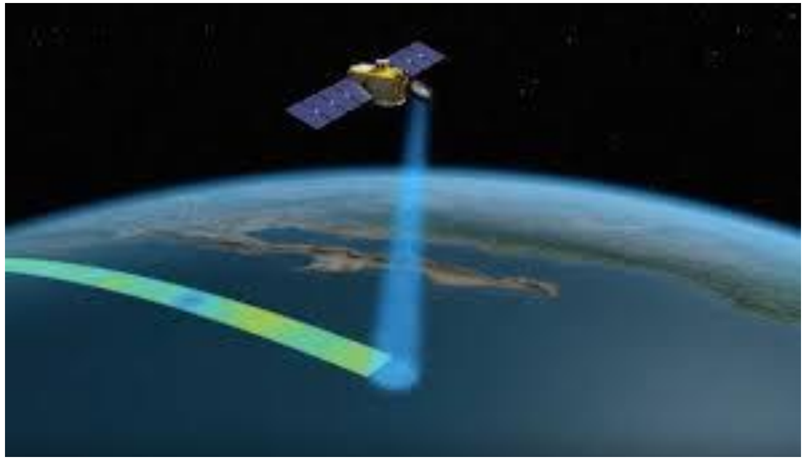
The quantity, quality and availability of observational datasets directly impact the quality of ocean analyses and forecasts and associated services

Assimilation from most global and regional systems is for: satellite altimetry, SST, ARGO and gliders

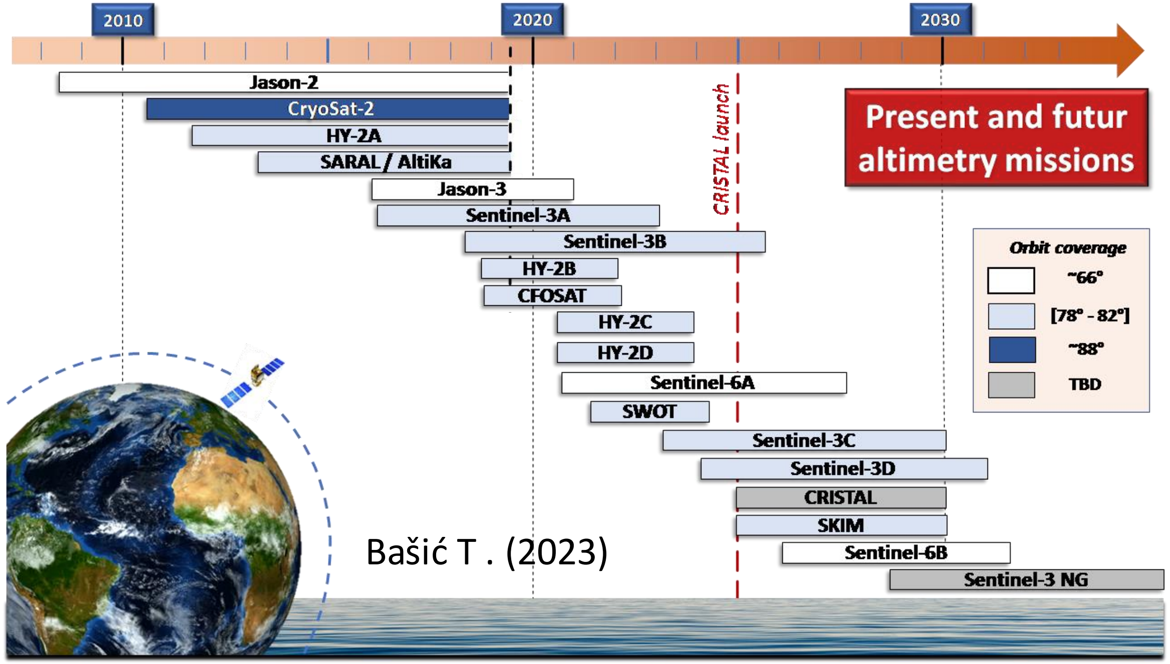
Observing Systems: Altimeters

Altimeters

- Are active radars: send a microwave pulse towards the ocean surface
- Measure:
  - The distance between satellite and sea surface: Altimeter range
  - The position of the satellite relative to a reference ellipsoid
  - The backscatter power related to surface roughness, wind and waves
- Have a precision of few centimeters for distance of 800-1300 km



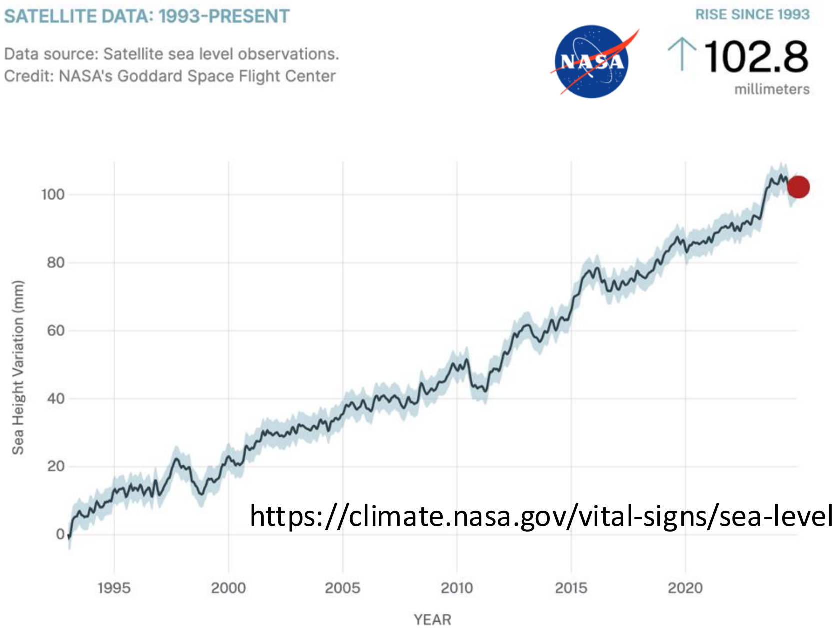
https://spaceflightnow.com/2016/03/19/jason-3-satellite-begins-surveying-worlds-oceans/



Bašić T . (2023)

Sea level rise :

- added water from melting ice sheets and glaciers
- expansion of seawater as it warms



https://climate.nasa.gov/vital-signs/sea-level

Observing Systems: Sea Surface Temperature Satellites

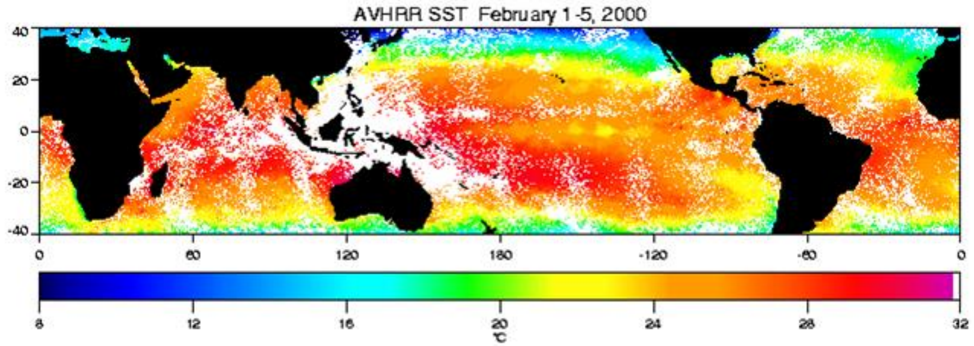
Principles of functioning: the instrument receives the radiation emitted by the surface that depends on the temperature of the surface or its molecular state.
→ methods for determining SST from satellite remote sensing include **thermal infrared** and **passive microwave** radiometry.

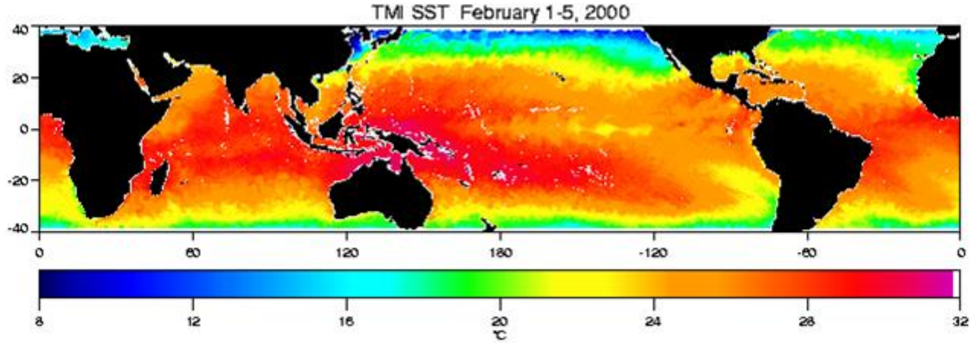
Thermal infrared SST measurements

PROS:
Long heritage (~30 years) & **High resolution**
CONS:
derived from radiometric observations at wavelengths of ~3.7 µm ~ 10 µm: Bands **sensitive to the presence of clouds,** aerosols, atmospheric water vapor
→ atmospheric correction and available for cloud-free pixels
→ maps of SST are often weekly or monthly composites

Passive microwave measurements

PROS:
Radiation is largely **unaffected by clouds** (easier to correct for atmospheric effects)
CONS:
Less accuracy and **resolution** wrt SST derived from thermal infrared measurements.
Affected by: wind-generated roughness at the ocean's surface and precipitation. These are corrected using multiple frequencies.





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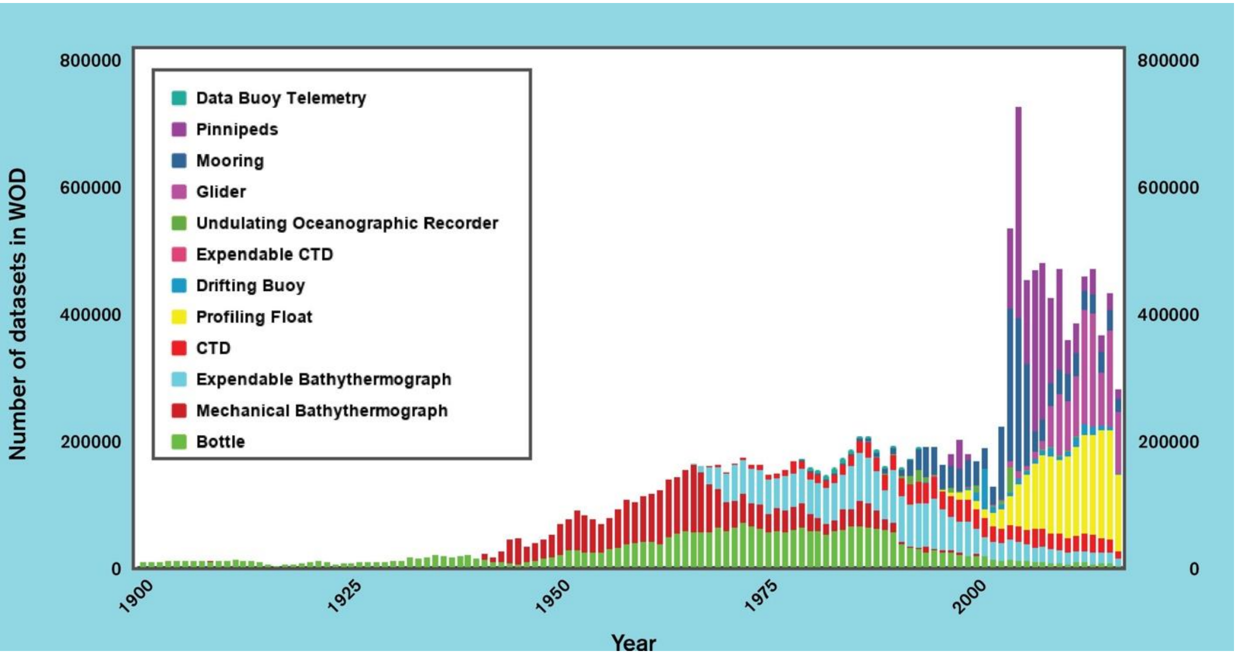
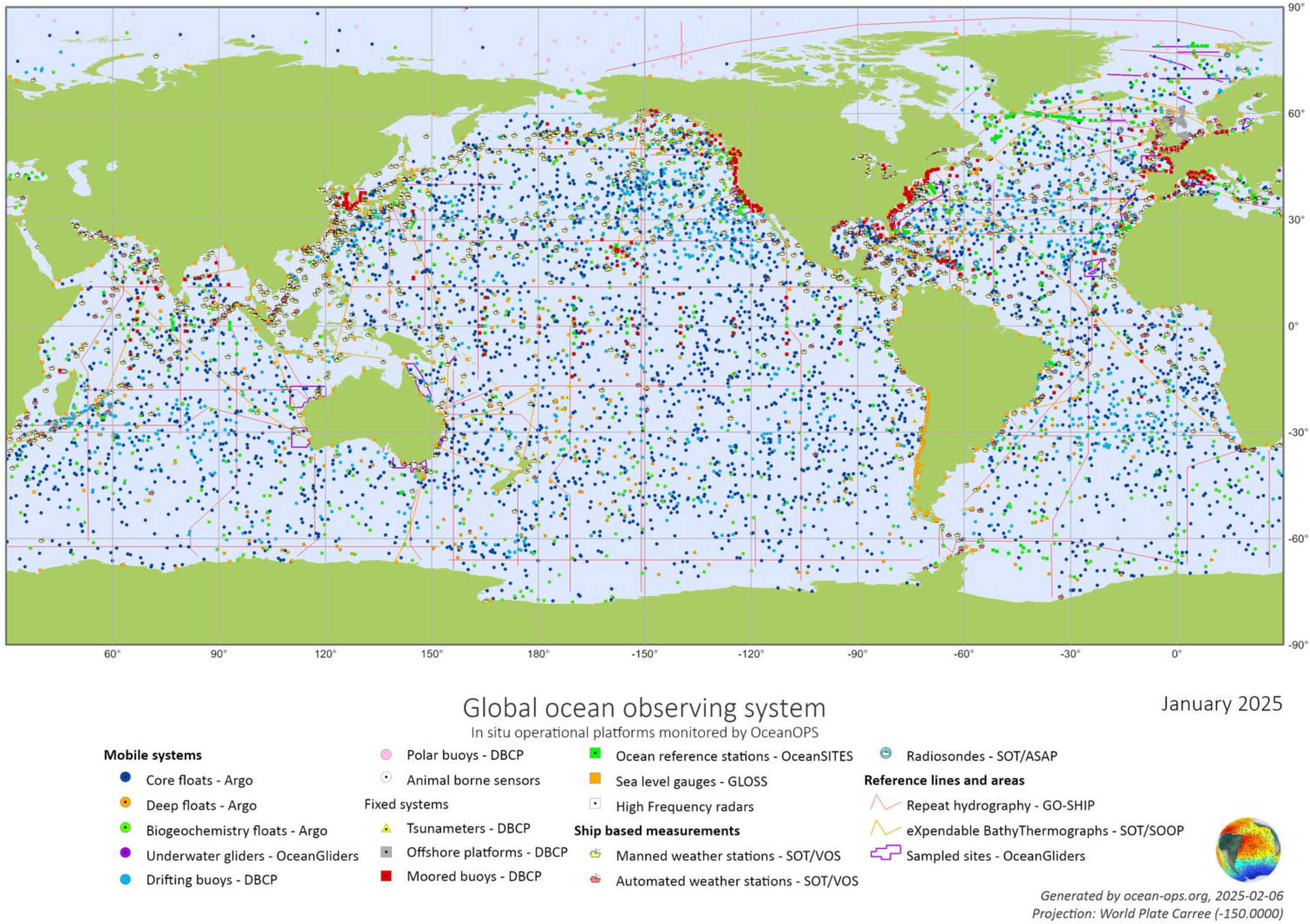
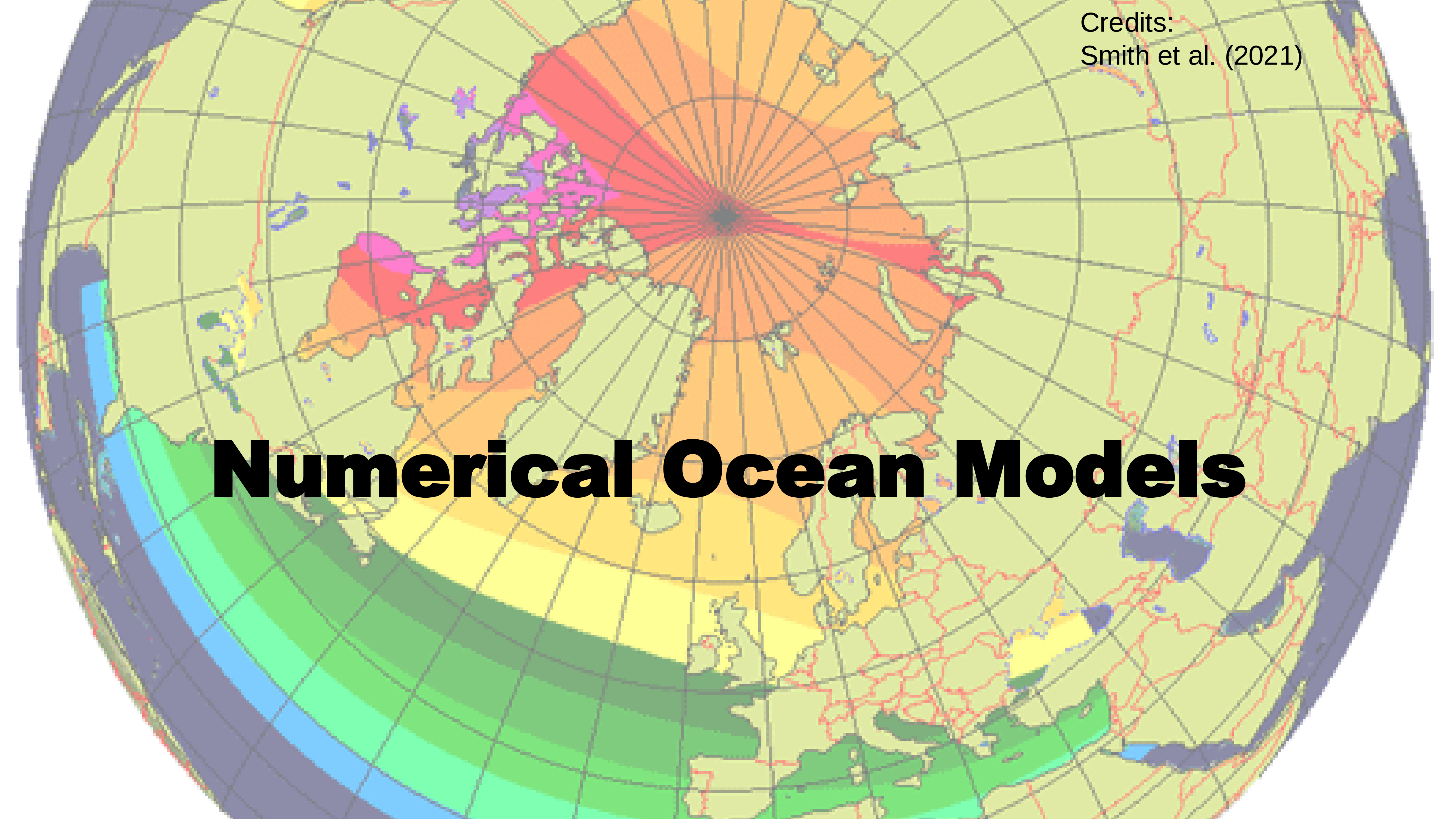
Observing Systems: In-Situ Measurements



Tanhua et al., 2019, https://doi.org/10.3389/fmars.2019.00440



From https://www.ocean-ops.org/ January 2025

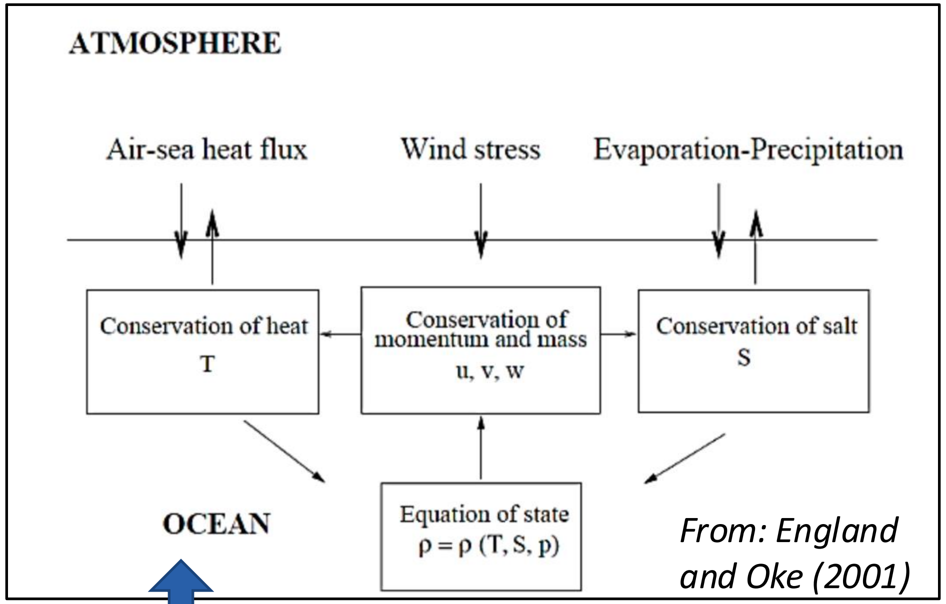


Numerical Ocean Models

Credits:
Smith et al. (2021)

Numerical Ocean Models

Primitive equations (Boussinesq, hydrostatic and incompressible) numerical ocean models at mesoscale resolution are the standard for forecasting



From: England and Oke (2001)

- Equations are interrelated
- Surface forcing required

Horizontal momentum equations:

$$\frac{du}{dt} - fv = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + F_u + D_u \quad (4.1)$$

$$\frac{dv}{dt} + fu = \frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + F_v + D_v \quad (4.2)$$

Hydrostatic approximation:

$$\rho g = -\frac{\partial p}{\partial z}$$

Equation of state
$\rho = \rho\,(T, S, p)$

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Conservation of heat:

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = F_T + D_T$$

Conservation of salt:

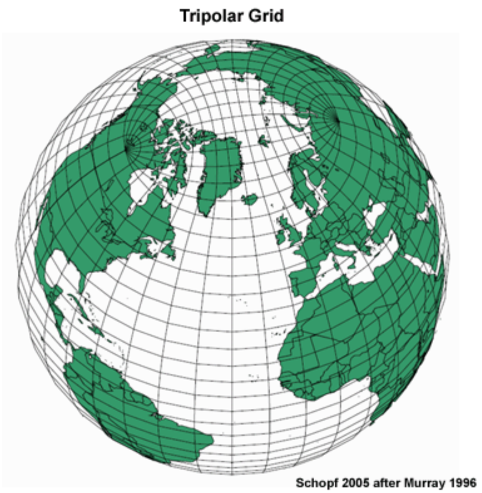
$$\frac{dS}{dt} = \frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} + v\frac{\partial S}{dy} + w\frac{\partial S}{\partial z} = F_S + D_S$$

Numerical Models: Spatial discretization

The Horizontal Discretization

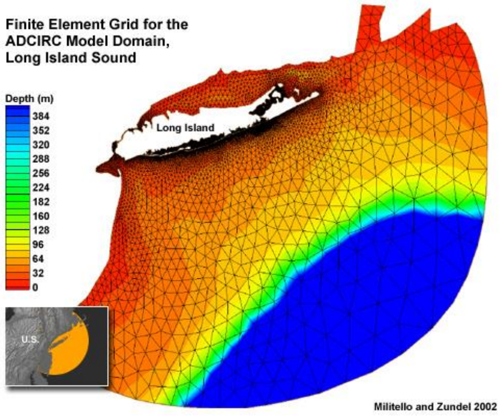
Regular grid: series of equally spaced lines. Earth is a sphere → lines tend to be curvilinear and their internal spacing varies

Grids problem when approaching the poles → **Tripolar grid**: circular grid over the arctic polar region (eliminating a north pole) with 2 points of grid convergence rather than one



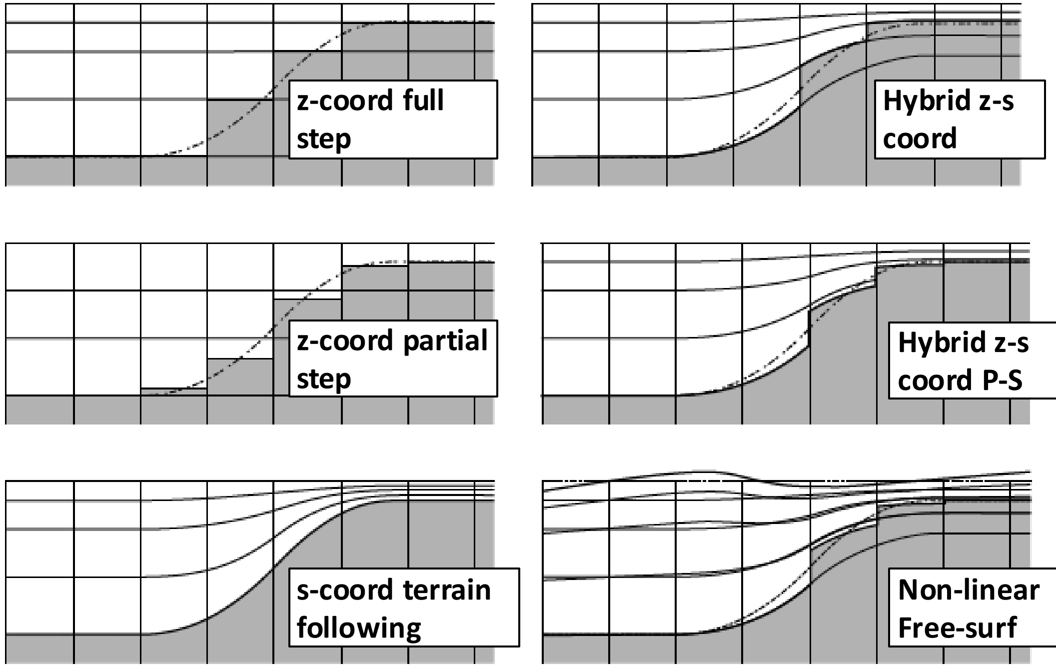
Irregular grid: composed of a series of (usually) triangles that can vary in size: **finite elements**

This allows to increase the resolution near the coast where small-scale processes are important, while keeping the resolution in the middle of the ocean relatively coarse.



The Vertical Discretization

Ocean surface → time dependent surface
The ocean floor depends on the geographical position (from more than 6Km to zero at the coast)
Ocean stratification exerts a strong barrier to vertical motions and mixing



Numerical Models: Initial Conditions

Initial conditions should be carefully specified: starting values for the variables that the model is going to predict, including: temperature, salinity, density, sea level, and velocity

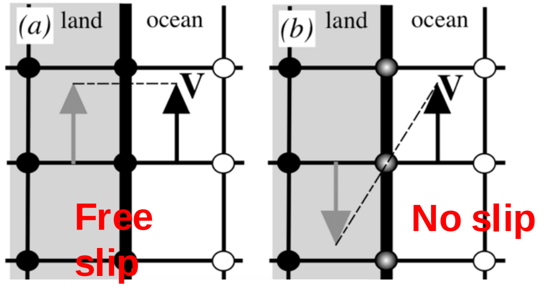
Climatologies: "consist of data averaged over well-defined spatial grids and over time periods such as month, seasons, or years. Climatologies provide boundary conditions and first-guess fields for models." (Fox, et al., 2002).
One way is to initialize models by using climatological values of T and S from databases and assuming the velocity field is zero at the start. The model physics will spin up a velocity field in balance with the density field. As forcing is applied, the velocity field will respond to it initially with transient flows that may not be realistic so usually rejected → **spin-up period**

Observational Data
Results from a data analysis system, can be used to initialize a model. This is the approach taken by some relocatable systems. It is difficult to use observations directly since they are so irregularly spaced and extensive error checking needs to be done.

Previous Model Run: initialize a model with fields from a previous run of that model, or with the results from another model. For instance, interpolating the results from a coarse grid model, to a finer grid to initialize a model for an area that needs to be implemented quickly.

Numerical Models: Lateral Boundary Conditions

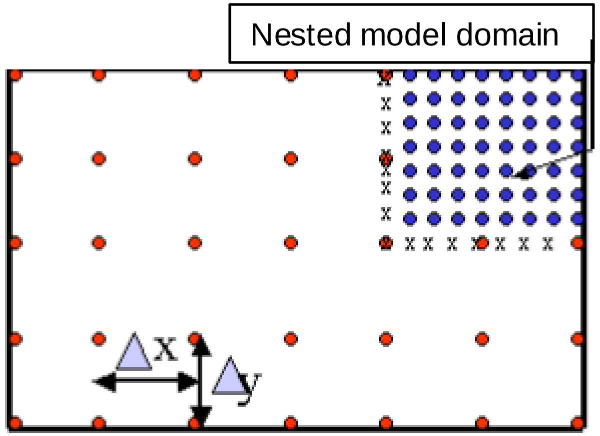
Initial conditions should be carefully specified for regional and local models



1.Closed boundary: No water flowing across the boundary (i.e. a coastline). Can be:

- ***no slip* (a)** in which there is no flow along the boundary, as well as through it
- ***free slip* (b)** in which there can be flow along the boundary, but not perpendicular, or normal, to it

2. Open Boundary: allow waves and disturbances originating within the model domain to leave it without affecting the interior solution. Also physical fields (sea level, T, S, velocity) should pass into the domain from the open boundary. Methods:



- ***Nested grids:*** values at the grid points from the larger coarser model are used as boundary conditions at the appropriate locations in the smaller nested model
- ***Specified boundary conditions:*** specified or prescribed i.e. using climatological values (constant or interpolated), observations, prescribed flow through Strait
- ***Radiative or sponge boundaries:*** usually an additional set of grid points is used outside the actual physical area of the model to help implement open boundary conditions. In a sponge boundary, the idea is to absorb outward propagating waves and energy rather than having it reflected back into the model domain.

3. Periodic or Cyclic Boundary Conditions: is appropriate for channel flow: what goes out one side comes back in on the other. This type of condition is often used to test models in development against known analytic solutions.

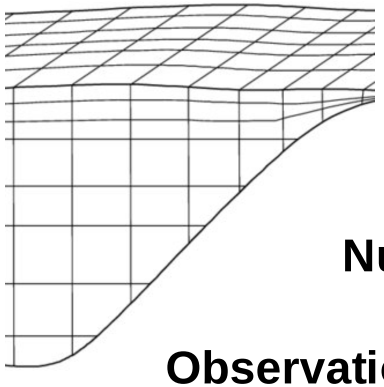
Operational Oceanography

INSITU OBSERVATIONS

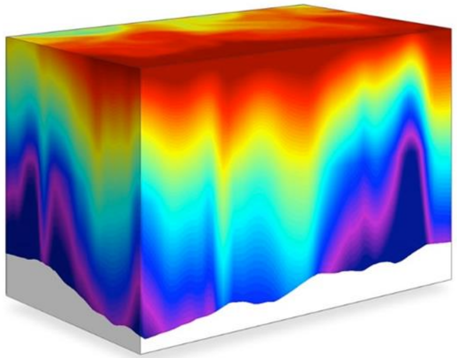
***Insitu* observations**
sample the water column BUT sparse coverage

SATELLITE OBSERVATIONS

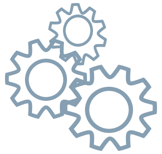
Along track and gridded **satellite observations**
cover a large part of the domain BUT limited to surface levels



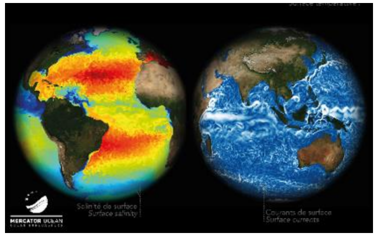
NUMERICAL MODELS



Numerical models provide time evolution of 3D properties of the ocean:
cover the entire ocean domain at a **defined resolution**.
Observations are assimilated to correct the model initial conditions: **ANALYSIS FIELDS**
Best initial conditions are used to initialize ocean model **FORECASTS**

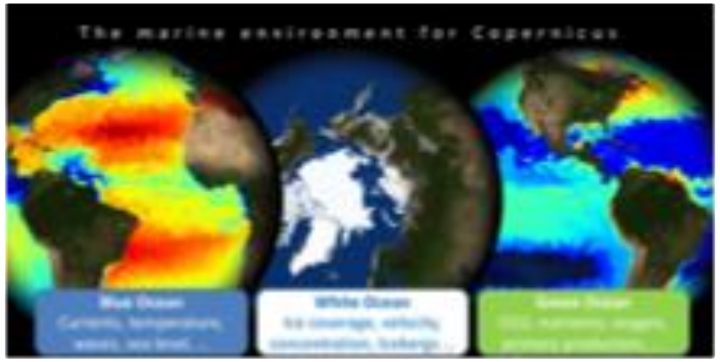


Operational numerical modelling systems provide routine and fully supported production and delivery of data



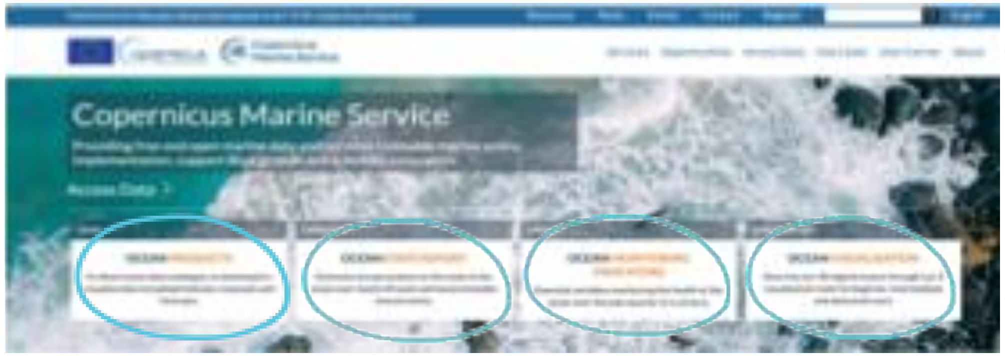
The Copernicus Marine Service

The Copernicus Marine Service provides free, regular and systematic authoritative information on the state of the **Blue** (physical), **White** (sea ice) and **Green** (biogeochemical) ocean, on **global** and **regional** scales.
It is funded by the European Commission (EC) and implemented by Mercator Ocean International



Copernicus Marine Catalogue

https://marine.copernicus.eu



Numerical Products

PAST:

Multiyear

Reanalysis: From 1993 (or before)

Interim: up to m-1

NEAR REAL TIME:

Analysis & Forecast

Analysis: - 2 years

Forecast: → 10 days

Observational Products

PAST:

Multiyear

Delayed Time

NEAR REAL TIME:

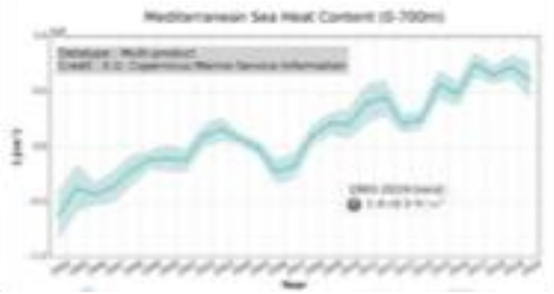
Close to present day

Ocean State Report

Contributing to the assessment of the state of the ocean

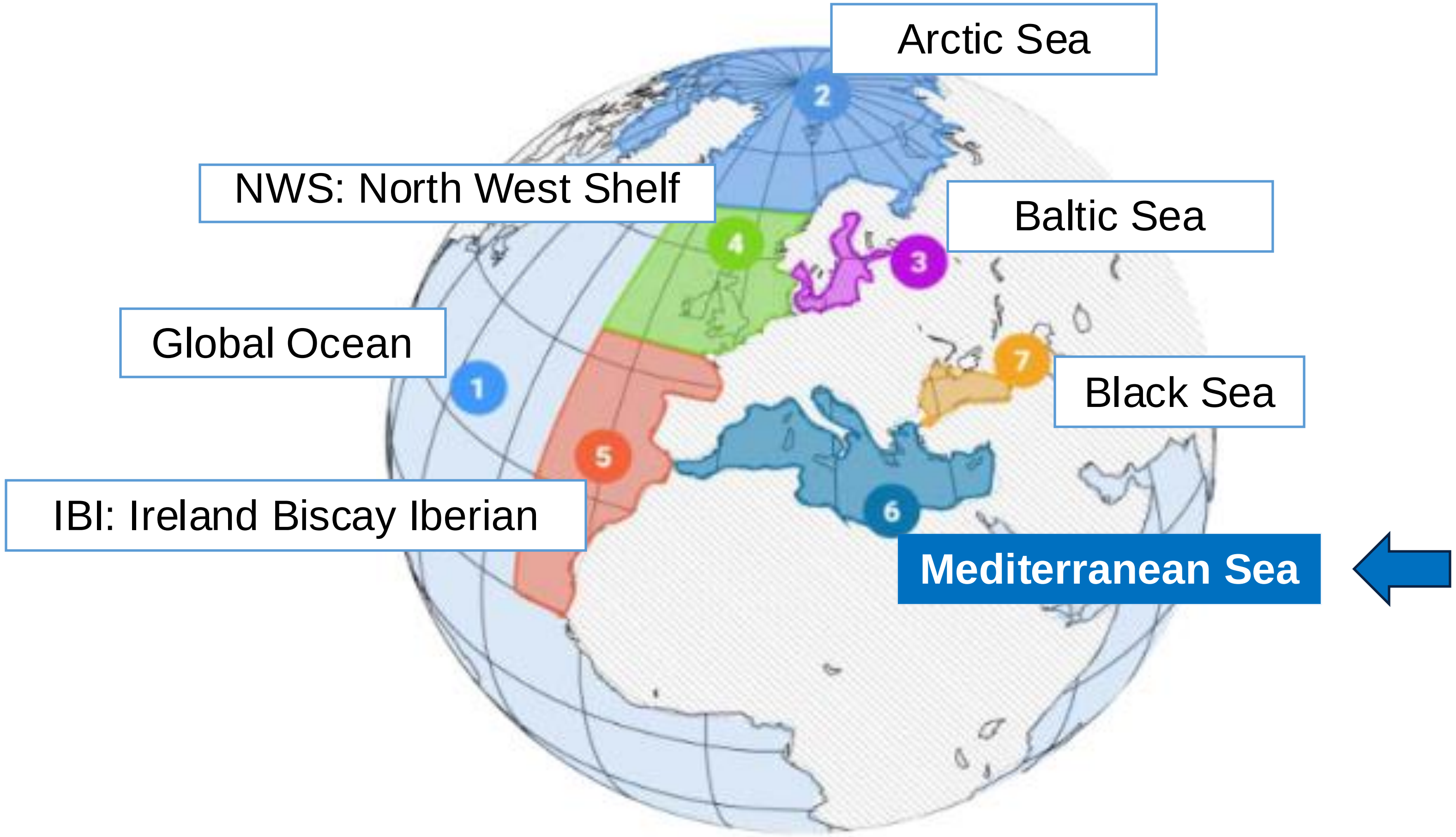
Ocean Monitoring Indicators

Producing Indicators to allow the continuous monitoring of the ocean



Copernicus Marine Monitoring and Forecasting Centers

7 MFCs – Monitoring and Forecasting Centres



The Copernicus Mediterranean Forecasting Center

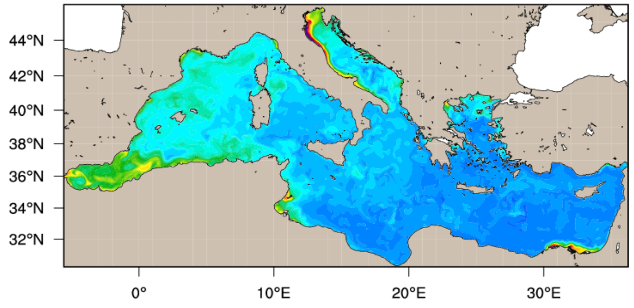
MED-MFC
~40 experts

The Med-MFC is one of the 7 MFCs
A consortium of 4 institutes

CMCC (Leader of the consortium and responsible for the Physical product) → **Med-PHY**
OGS (Responsible for the Biogeochemical product) → **Med-BIO**
HCMR (Responsible for the Wave product) → **Med-WAV**
CINECA Support to operational production (new from 2022)

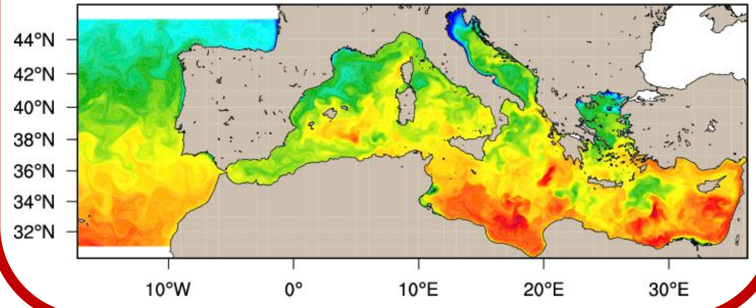
Med-Biogeochemistry PU

OGS



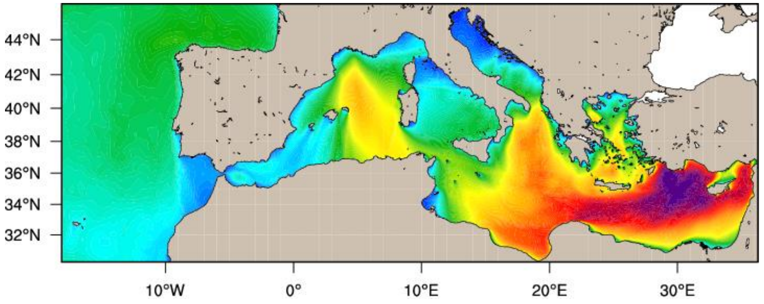
Med-Physics PU

cmcc Centro Euro-Mediterraneo sui Cambiamenti Climatici



Med-Waves PU

hcmr ΕΛΚΕΘΕ

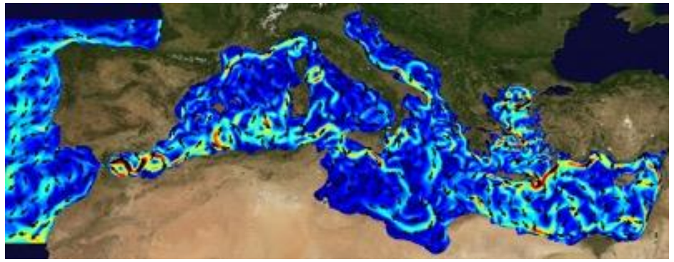


The modelling systems are based on **state-of-the-art community models**, **assimilate *insitu* and satellite observations** and are forced by **high resolution atmospheric fields**.

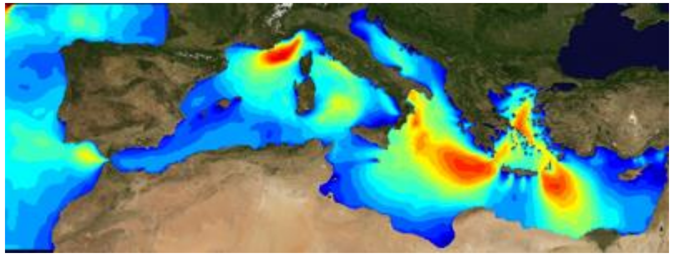
Improvements and functioning of the Med-MFC systems are based on the **full consistency among the three components** which **are jointly upgraded** and include a **continuous amelioration** of the accuracy of the products.

The Copernicus Mediterranean Physical Forecasting System

Ocean General Circulation Model (OGCM) based on NEMO v4.2 (tides)

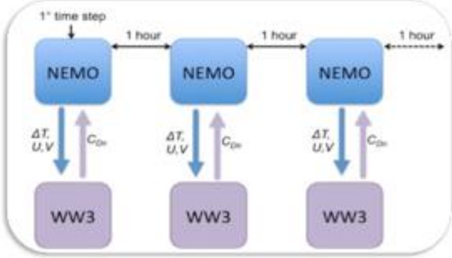


Wave model
WaweWatch-III (WW3) v6.07



2-way hourly coupling **OASIS**

Hor. Res. = **1/24º (~4 km)**
Vert. Res. = **141 z* vertical levels** with partial cells



Hor. Res. = **1/24º (~4 km)**
Spectral discretization:
* 30 freq. bins (0.05-0.79 Hz)
* 24 directional bins

The two-way coupling consists of inputting:
Currents (for wave refraction) and **air-sea temperature difference** (for wind speed correction) to the wave model
and
providing the **neutral surface drag coefficient** from waves used to compute the wind stress in NEMO

The Forcing fields

ECMWF 1/10° atmospheric fields (through Italian Air Force Meteorological Service):

- MSLP, cloud cover, 2m relative humidity
- 2m T, 10m Wind , Precipitations

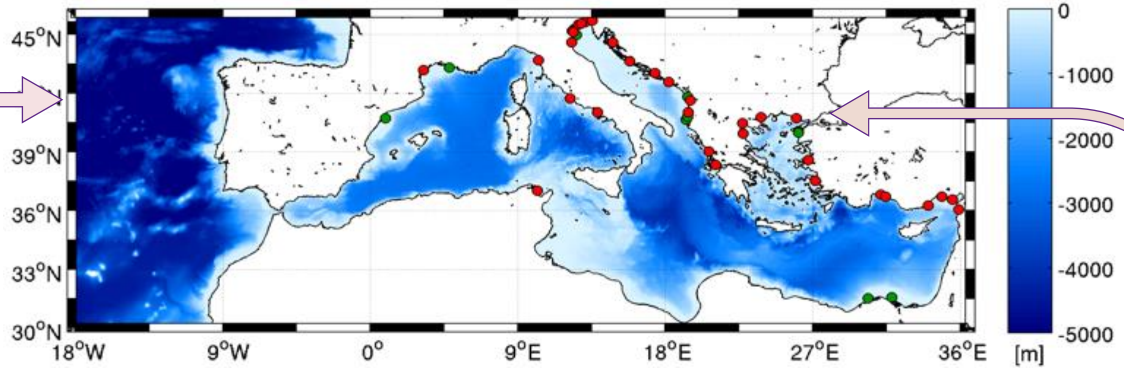
Temporal resolution:

Forecasts: 1hr – 3hrs – 6 hrs

Analysis: 6 hours time resolution

Land river runoff:

Surface boundary condition for **39** major rivers with annual mean discharge > 50 m^3/s using EFAS daily mean values



Lateral Boundary conditions in the Atlantic:

Daily NRT analyses and forecasts from Copernicus Global Ocean Forecasting System (GLO-MFC) @ 1/12° horizontal resolution, 50 vertical levels

Lateral Boundary conditions in the Dardanelles Strait:

Turkish Straits System (TSS) box model (Maderich et al. 2015) daily climatologies

\+

Temperature from GLO-MFC

The assimilated data

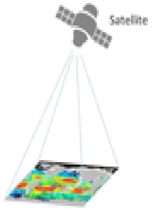
Model solutions are corrected by using observations

Satellites and insitu observations are jointly assimilated using a **3D variational scheme (OceanVar)** adapted to the oceanic assimilation problem with a daily cycle

The assimilated data are:

Along track Sea Level Anomaly

- Jason 3
- Cryosat2
- Saral/AltiKa
- HY-2B
- Sentinel3A/B-6



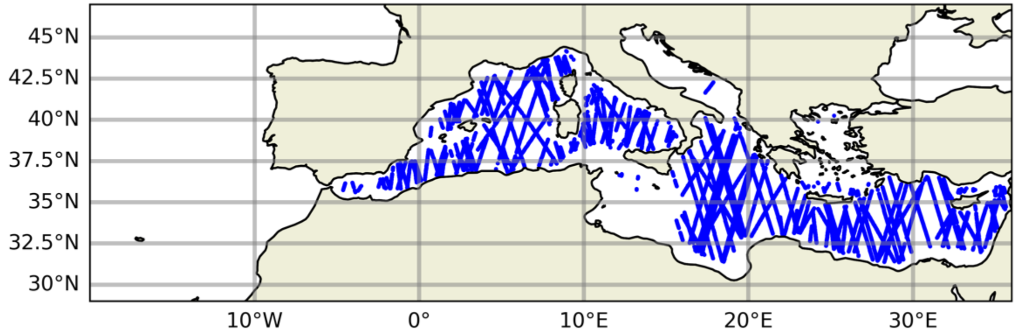
Vertical profiles of Temperature and Salinity:

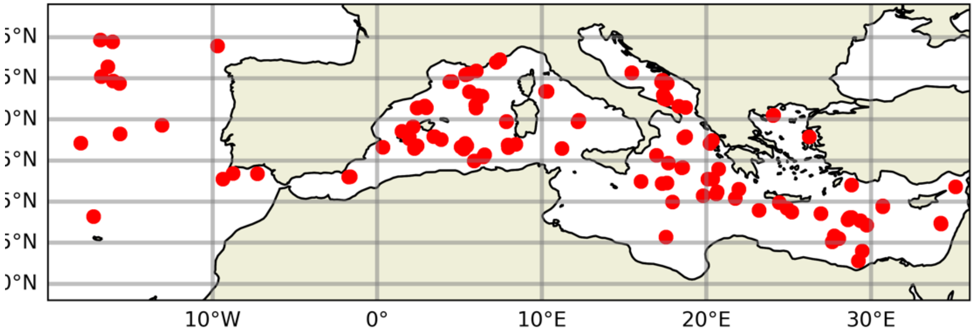
Argo

Gliders

XBT

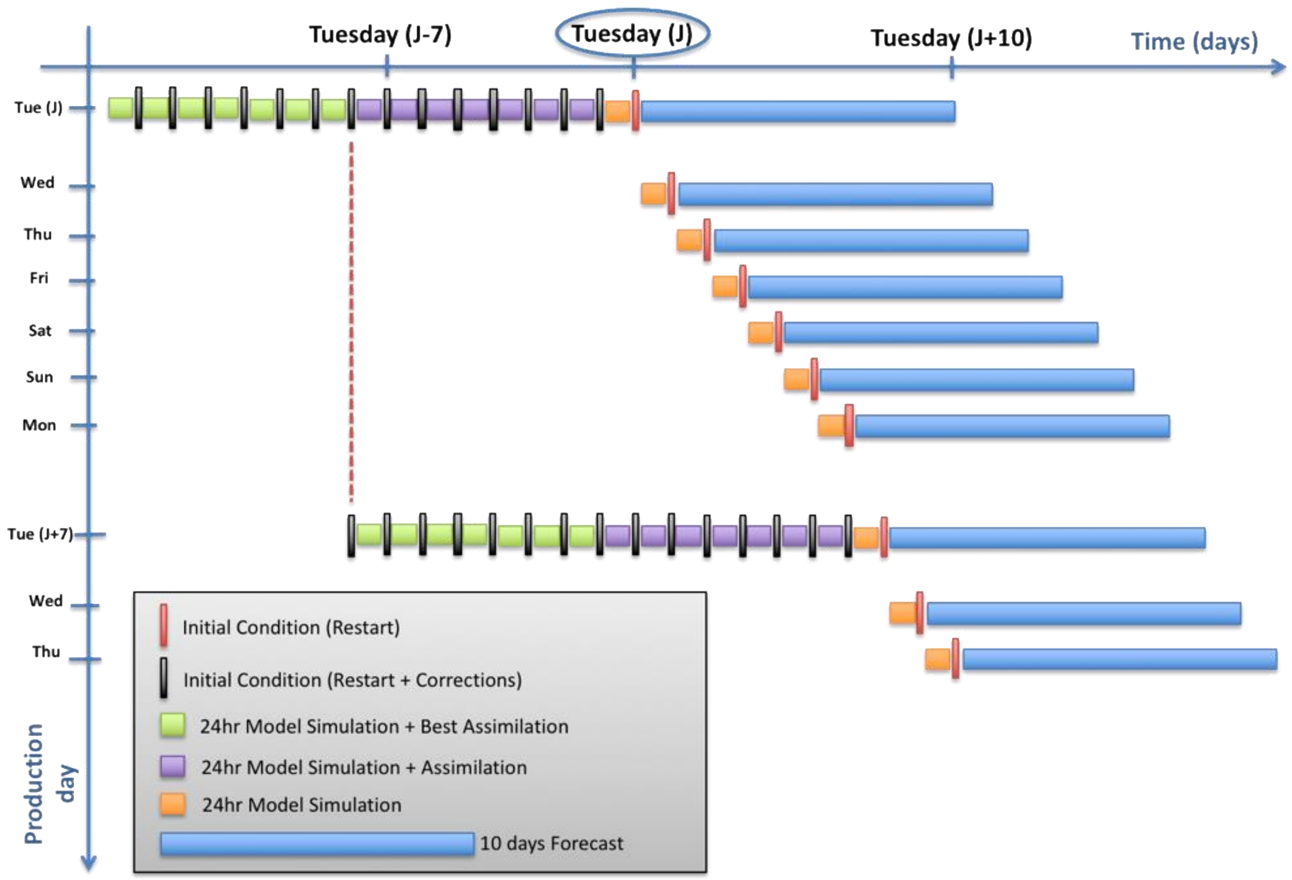
Non-solar heat flux correction is achieved through satellite SST nudging





# of assim. obs. in 1 week

The Operational Chain

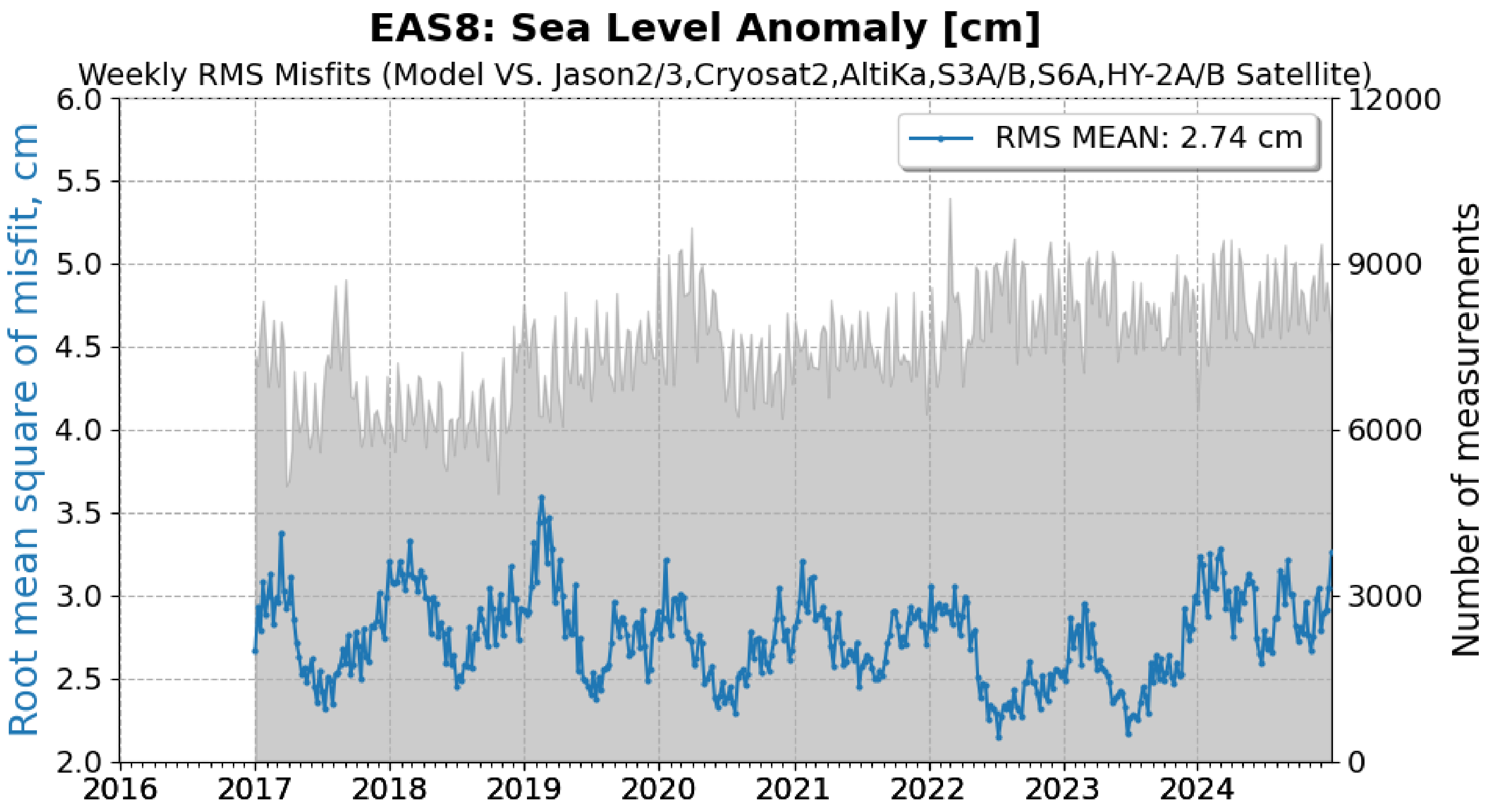


ANALYSIS: Each Tuesday: simulation for the previous 2 weeks with ECMWF analysis atmospheric forcing + assimilation correction

SIMULATION: Every day the initial condition for the forecast cycle is generated by a model simulation for the previous 24hr hours and forced by ECMWF analysis fields

FORECAST: Computed for the next 10 days forcing the numerical model with ECMWF forecast fields

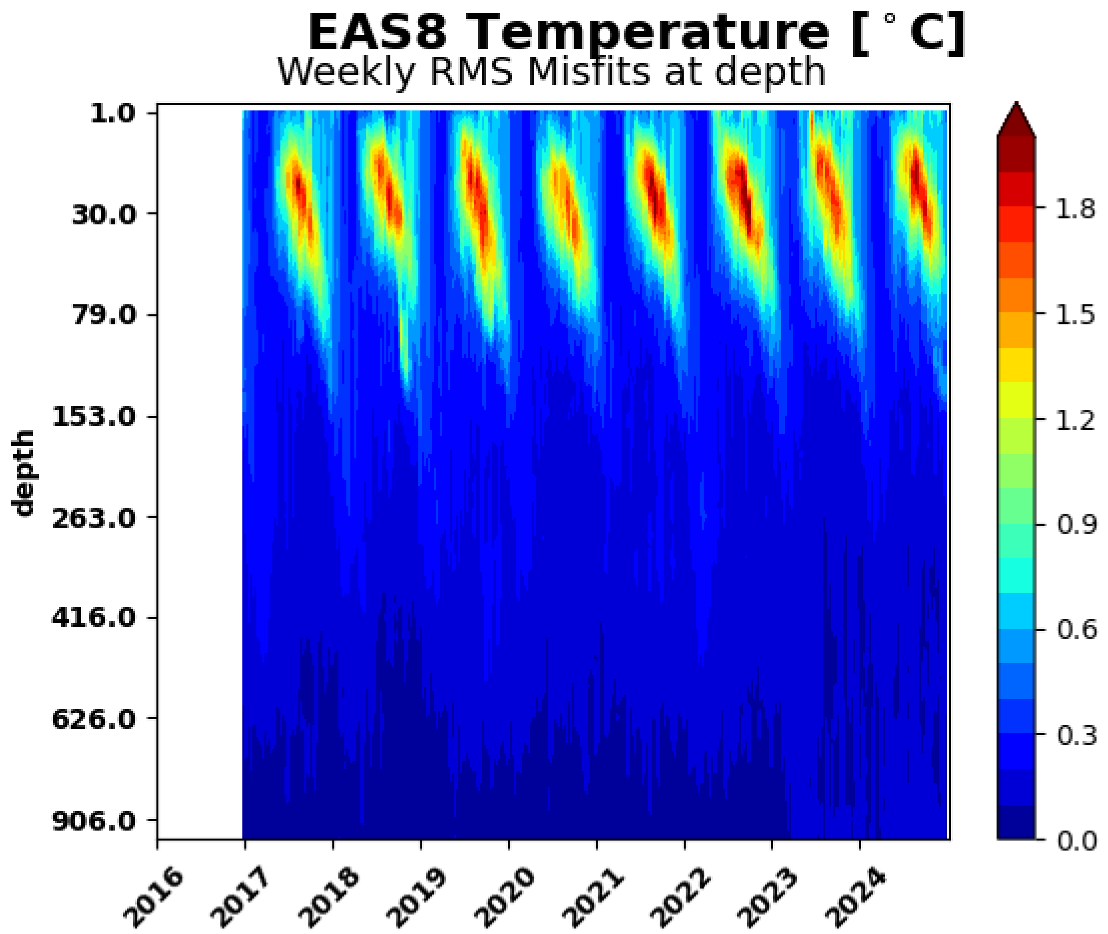
The model validation

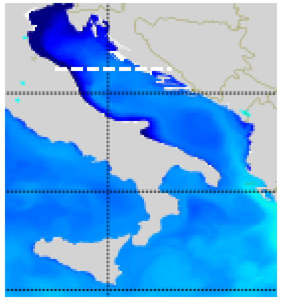


Model Sea Level is compared to Sea Level Anomaly from Satellite data

Average error ~2.7 cm
Averaged in the whole Mediterranean Sea in the period [2017-2024]

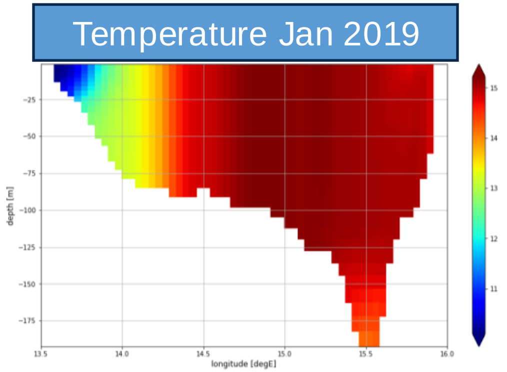
The model validation

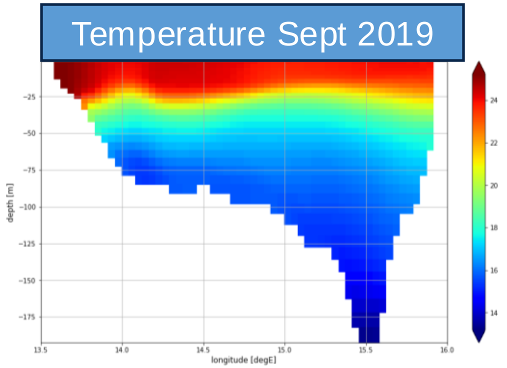




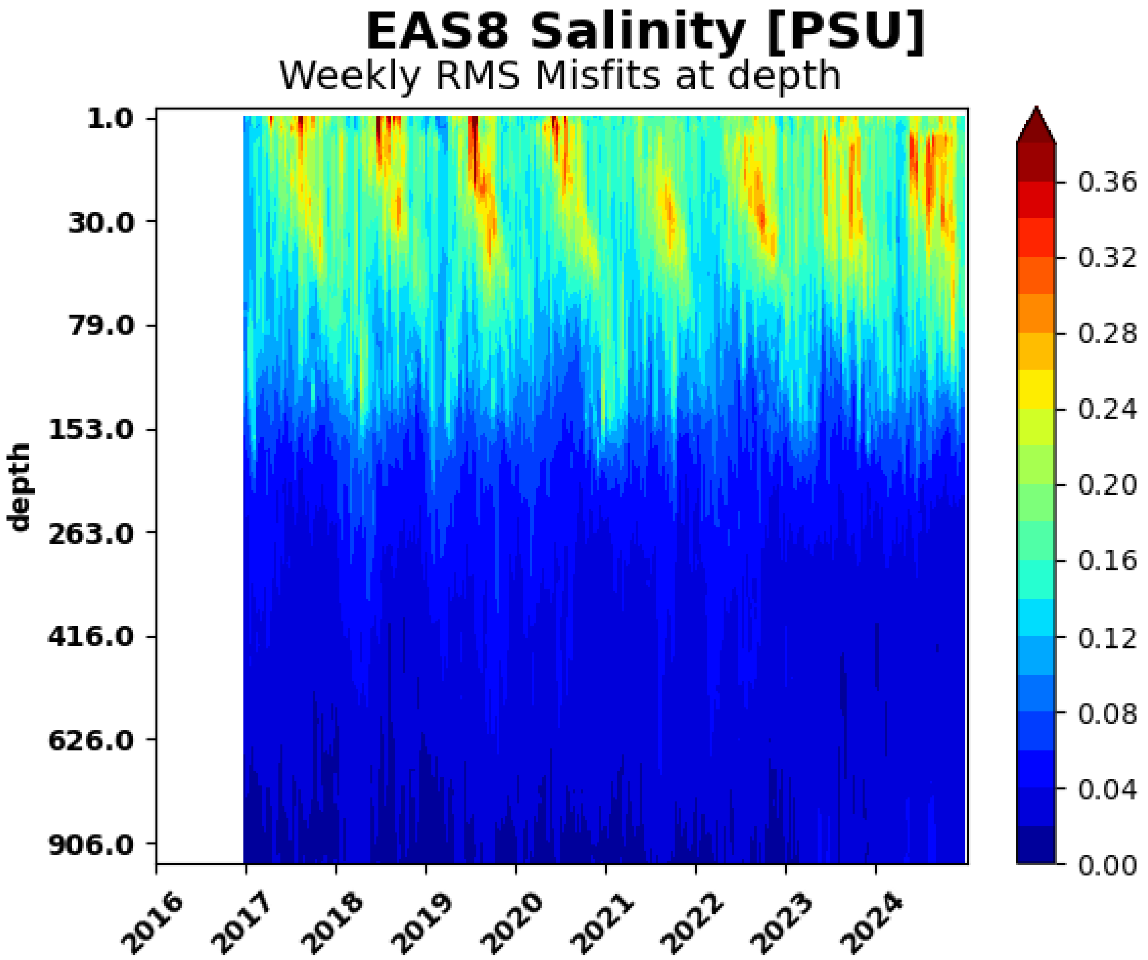
Model Temperature is compared to vertical profiles of ARGO floats, Gliders and XBTs in-situ data

Maximum error in late summer/autumn





The model validation

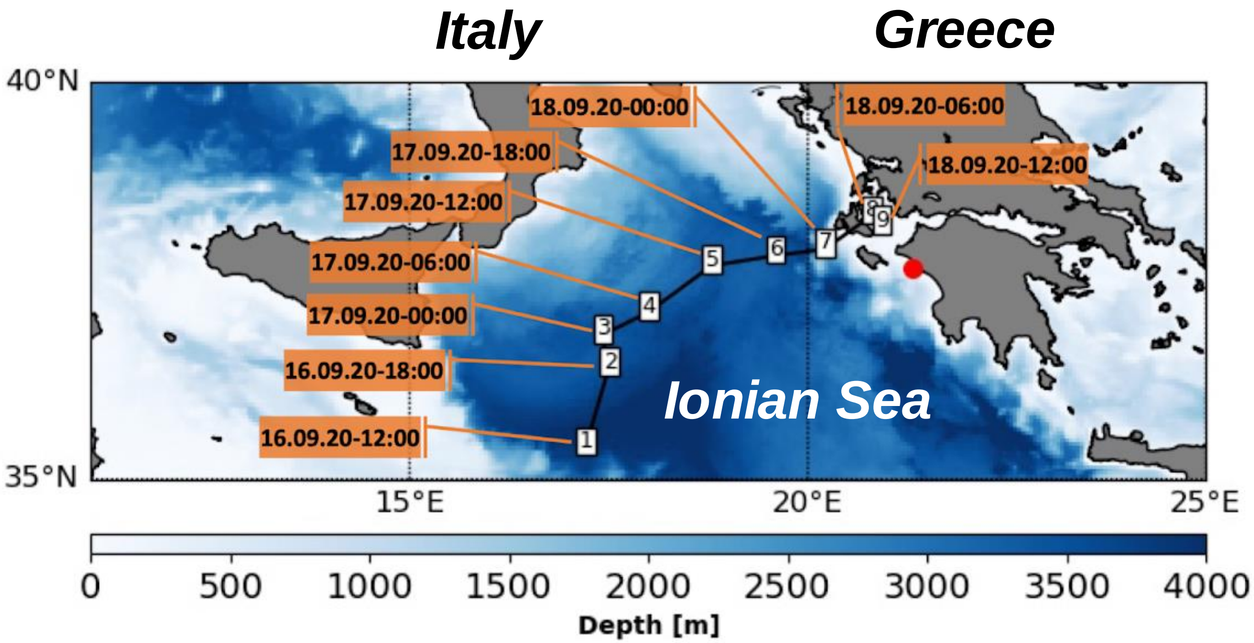


Model Salinity is compared to vertical profiles of ARGO floats and Gliders in-situ data

Maximum error in late summer/autumn

Application: Medicane Ianos

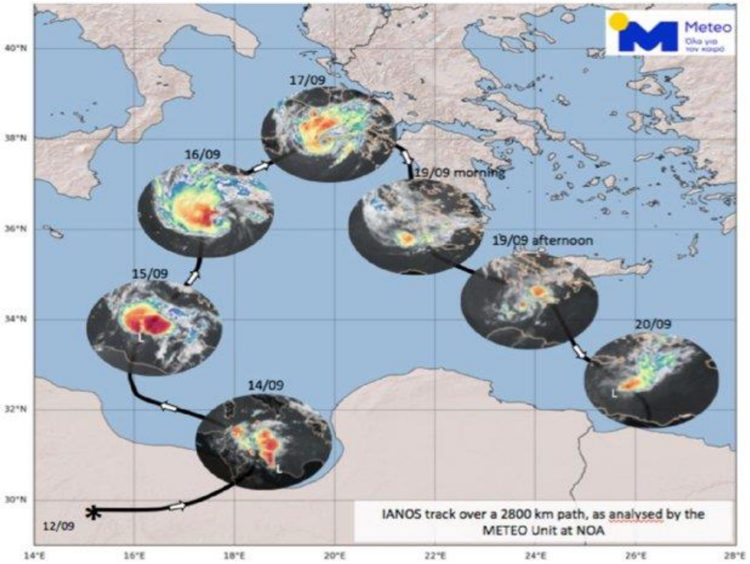
- A record Mediterranean tropical-like cyclone
- 14th to 20th September 2020
- Impacting Ionian Sea & Greece
- Wind speeds up to 110 km/h, torrential rain and flooding → damages and death
- One of the strongest such storms recorded since 1969 (beginning of satellite observations) in terms of duration and intensity



Investigating the cyclone impacts by using observational data may have some obvious limitations → 3D ocean models can provide insights on its evolution and on the coupling mechanisms driving ecosystem productivity

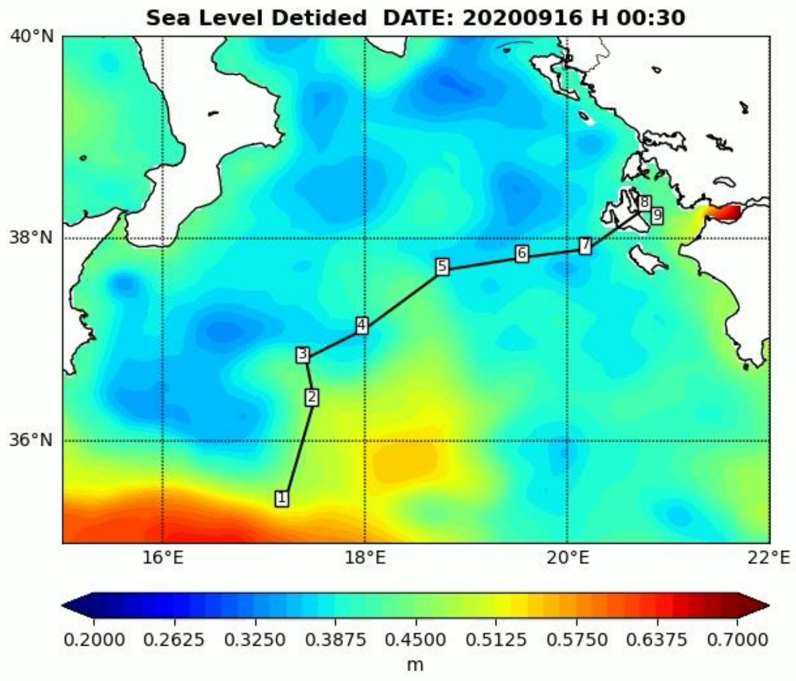
Med-MFC numerical analysis data are used to analyse Ianos impacts on the physical, wave and biogeochemical upper layers fields

Ianos track as analyzed by the METEO unit of IERSD/NOA

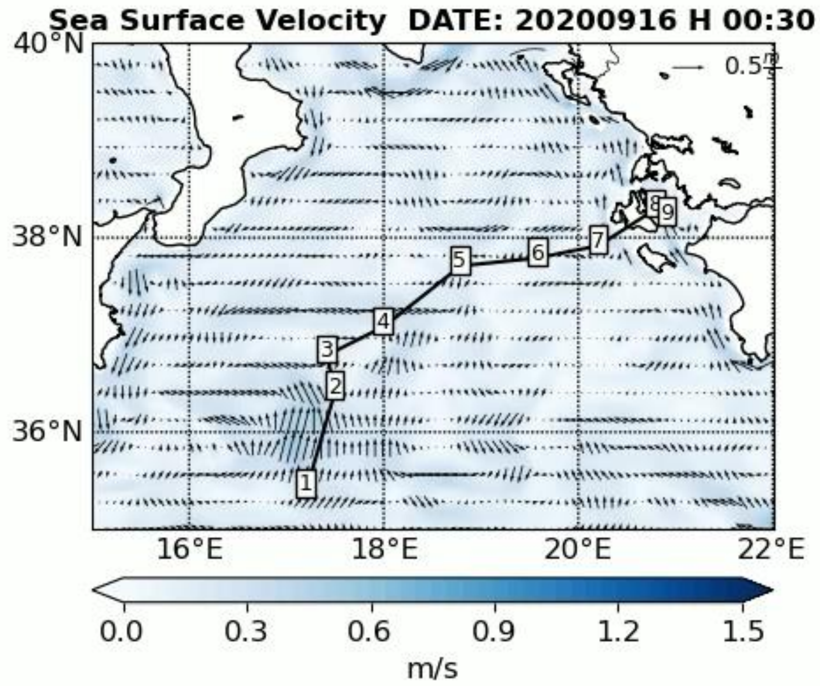


Application: Medicane Ianos Evolution

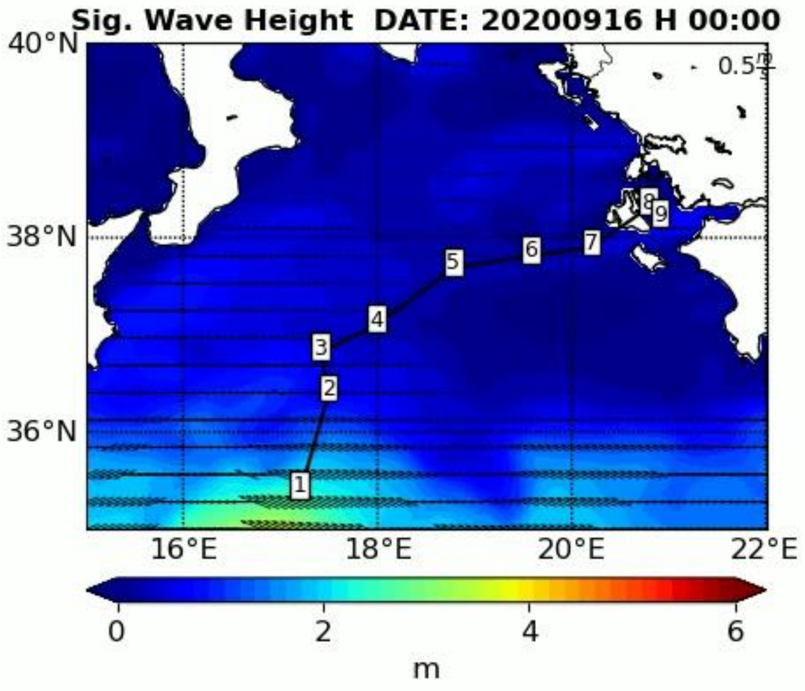
SEA LEVEL



SURFACE CURRENTS



SIG. WAVE HEIGHT



Impact of Medicane Ianos' passage clearly captured by hydrodynamic and wave models

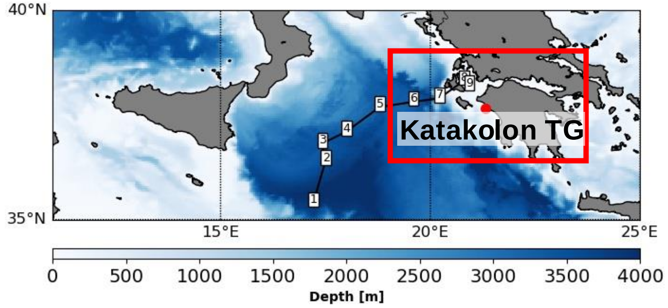
→ increase of the sea level and significant wave height

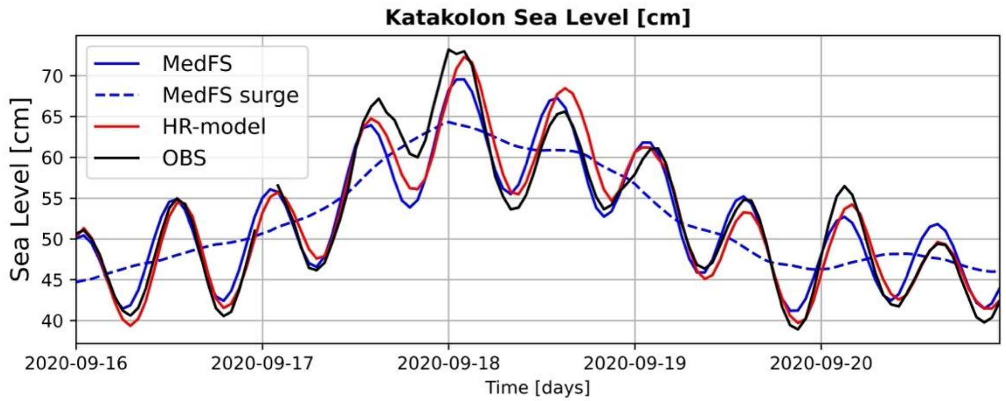
→ intensification of the surface currents

along the Medicane path

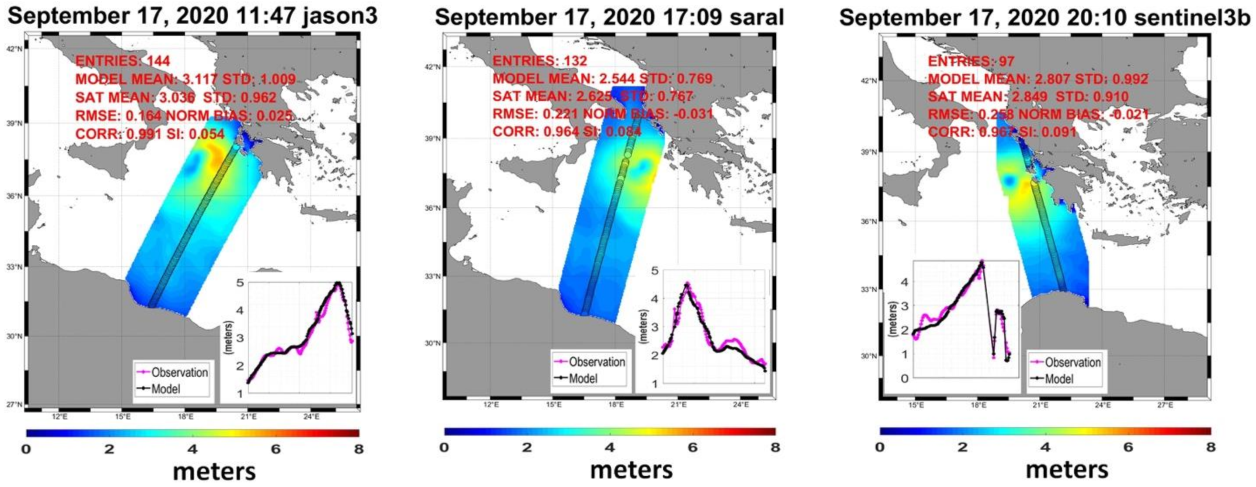
Application: Model comparison with Observations

SEA LEVEL





SIG. WAVE HEIGHT



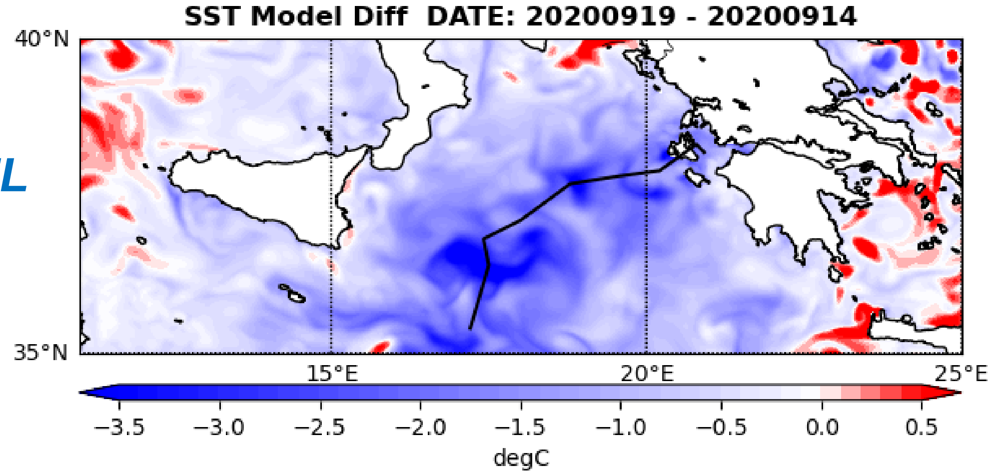
- The accuracy of the modelled sig. wave height is very good
- Correlation between the observed and modelled data ranges from 0.96 to 0.99
- Model bias is close to zero

- Model hourly sea level in agreement with observations @ Katakolon TG
- Model Underestimation ~ 4 cm at peak
- MedFS used to force high res. (3km to 100m) unstructured grid model (based on the SHYFEM) → reduced error at peak

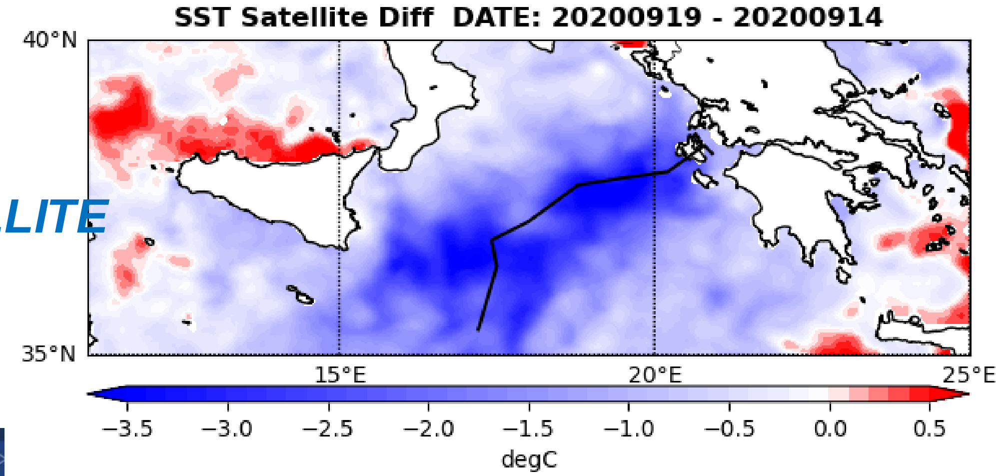
Application: Model comparison with Observations

SEA SURFACE TEMPERATURE DECREASE BETWEEN 19 & 14 SEPT. 2020

MODEL



SATELLITE



Model Sea Surface Temperature decrease in agreement with satellite observations

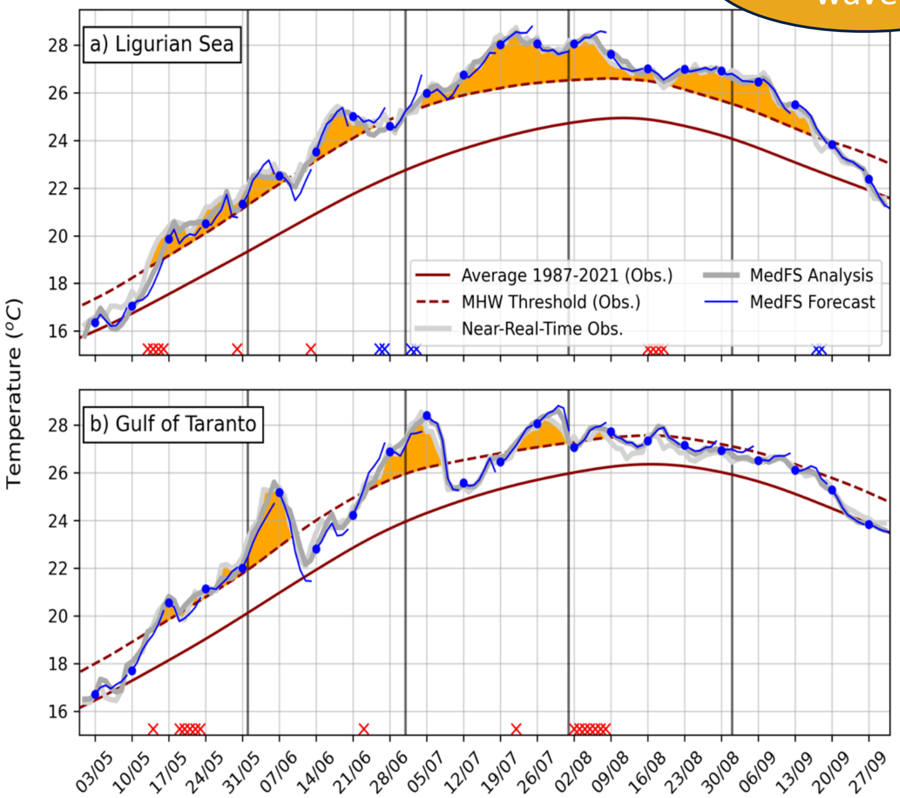
- SST decrease around -3.5 °C
- MedFS shows some underestimation compared with the satellite L4 SST dataset
- The observational dataset could not represent the small scale features present in the model solution due to the scarcity of direct observations (cloud covering) → SST L4 is a combination of a first guess field with available data from previous days

cmcc

MedFS Forecasting Extreme Events

SST & Marine Heat Waves
Summer 2022

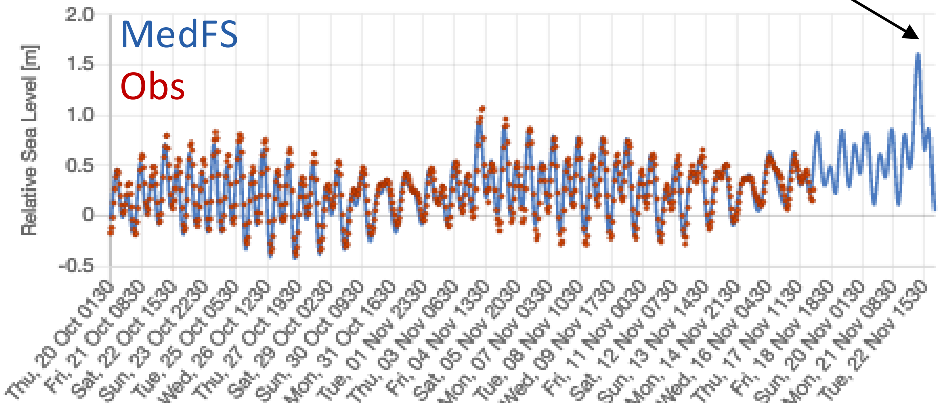
Marine Heat waves



MedFS **predicting Marine Heat waves**

Mc Adam et al. (2024)

Venice Acqua Alta
November 2022



https://medfs.cmcc.it/

MedFS **predicting Acqua Alta events** in Venice with 3 days in advance

Ocean Forecasting Systems value

- Forcing fields to higher resolution and coastal models, support to coastal monitoring
- Safety and disaster, i.e. search and rescue, oil spill forecast, Port Operations
- Water quality assessment, Protection and management of marine ecosystems
- Marine navigation / transportation
- Natural resources and energy
- Oil and Gas industry
- Marine food, Fishery and Aquaculture sector
- Maritime sports & Tourism industry
- Civil protection, Coast Guard
- General public
- Research community
- Good Environmental State assessment
- Blue Economy
- Climate change (e.g. acidification, regime shifts)
- ……

Thanks

Emanuela Clementi
emanuela.clementi@cmcc.it

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