COASTAL RESILIENCE SCHOOL

Enhancing Coastal Ocean Modelling: Towards an Integrated, Realism-Augmented Framework

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Bertinoro (ITA) 08/04/2025

unesco Intergovernmental Oceanographic Commission

UN Decade Collaborative Centre for COASTAL RESILIENCE

OTG@ OceanTeacher Global Academy

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Coastal Hazards and risks

Coastal regions face numerous hazards and risks due to their dynamic environments and exposure to natural and anthropogenic pressures.

Physical

Extreme waves
Storm surges and coastal flooding
Extreme weather events
Erosion
Sea level rise

Socio-economic

Damage to infrastructure
Economic losses
Population displacement
Loss of human lives

Bio-Ecological

Loss of biodiversity and ecosystem services
Coastal pollution
Eutrophication
Habitat degradation

Only 15% of the world's coastlines remain in their **natural state**, while **40% of the global population resides within 100 kilometers of a coast**.

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Physical Hazards

but before going ahead…

What is the sea level?

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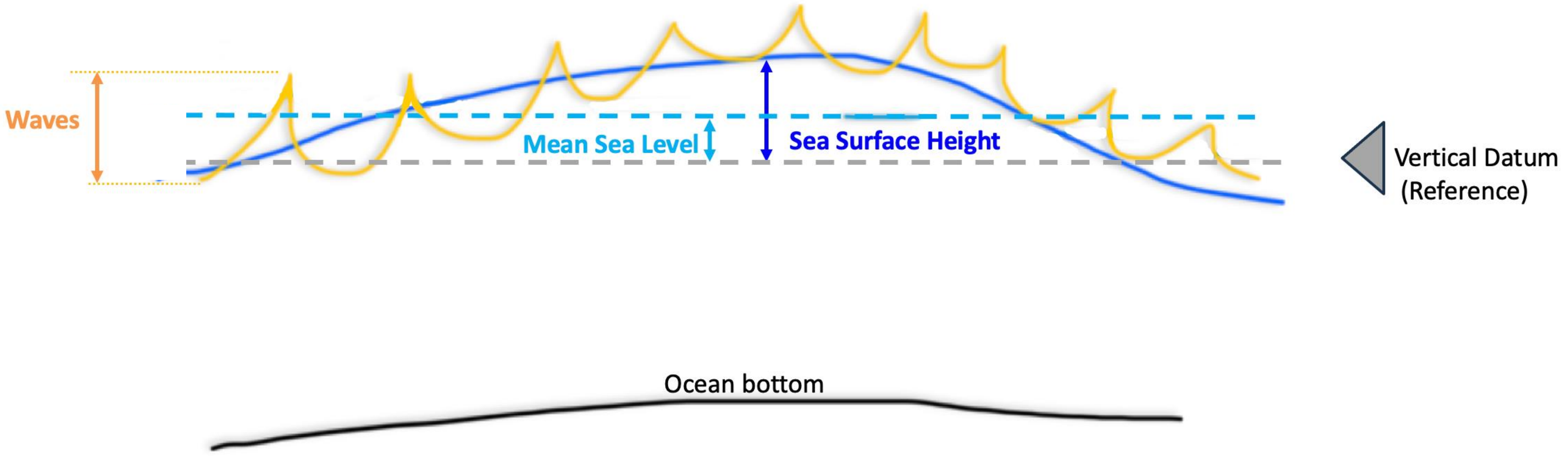
Sea level

Height of the ocean surface relative to a reference level, often the geoid or an ellipsoid. It includes contributions from tides, ocean circulation.
Variations occur over **long spatial and temporal scales** (from kilometers to thousands of kilometers, and from few hours to years).

Waves

Generally referred to ordinary gravity waves.
Waves are short-period oscillations of the sea surface caused by wind, gravity. They are described by parameters like **significant wave height (SWH)**, **wave period**, and **wave direction**.
Generated mainly by **wind stress** over the ocean surface.
Act on **small spatial and temporal scales** (tens of meters and seconds).



Total water level

Total Water Level

= Storm Surge (from atm.)

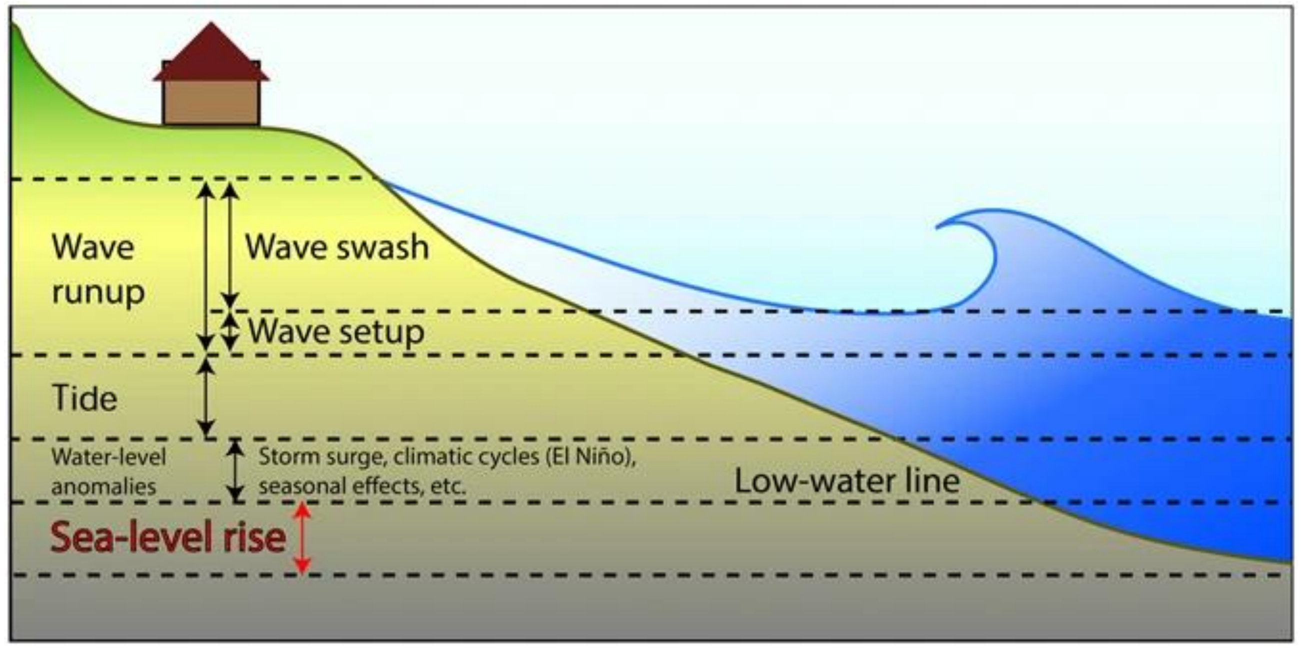
+ Tides

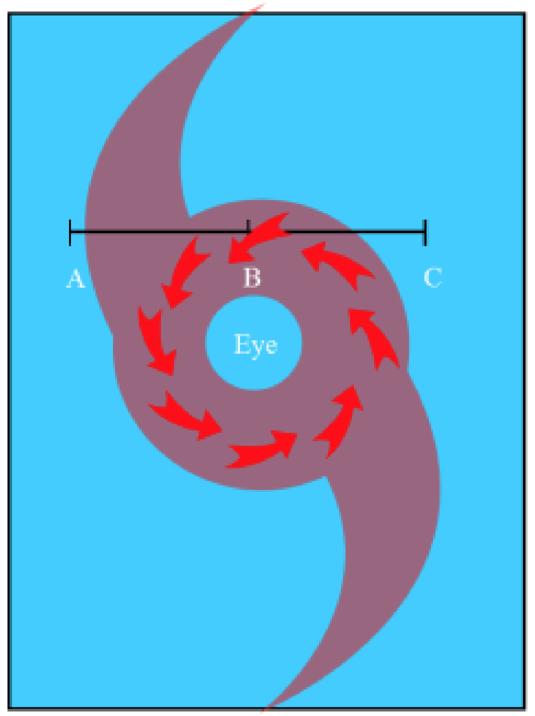
+ Waves

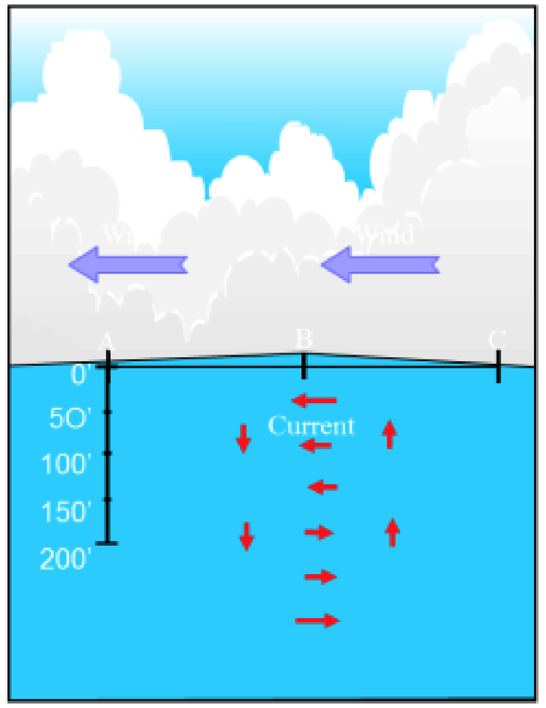
+Freshwater Input

+ Currents

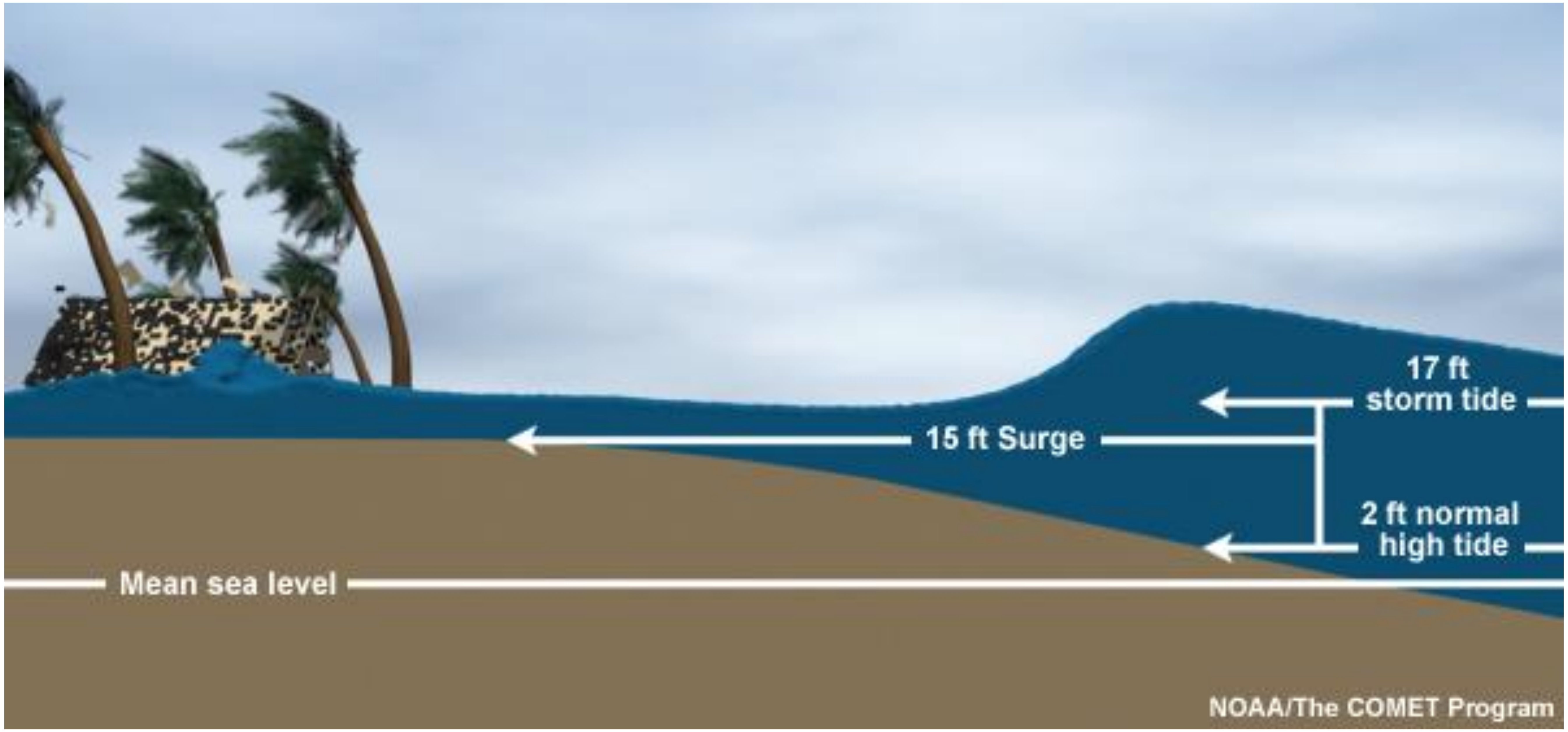
+Thermo-halosteric effect







What is a storm surge?



Storm surge is tsunami-like phenomenon, an abnormal rise of water generated by a storm over and above the predicted astronomical tide. Storm surge is caused primarily by the **strong winds** over the ocean (i.e. due to hurricane or tropical storm), but NOT only.

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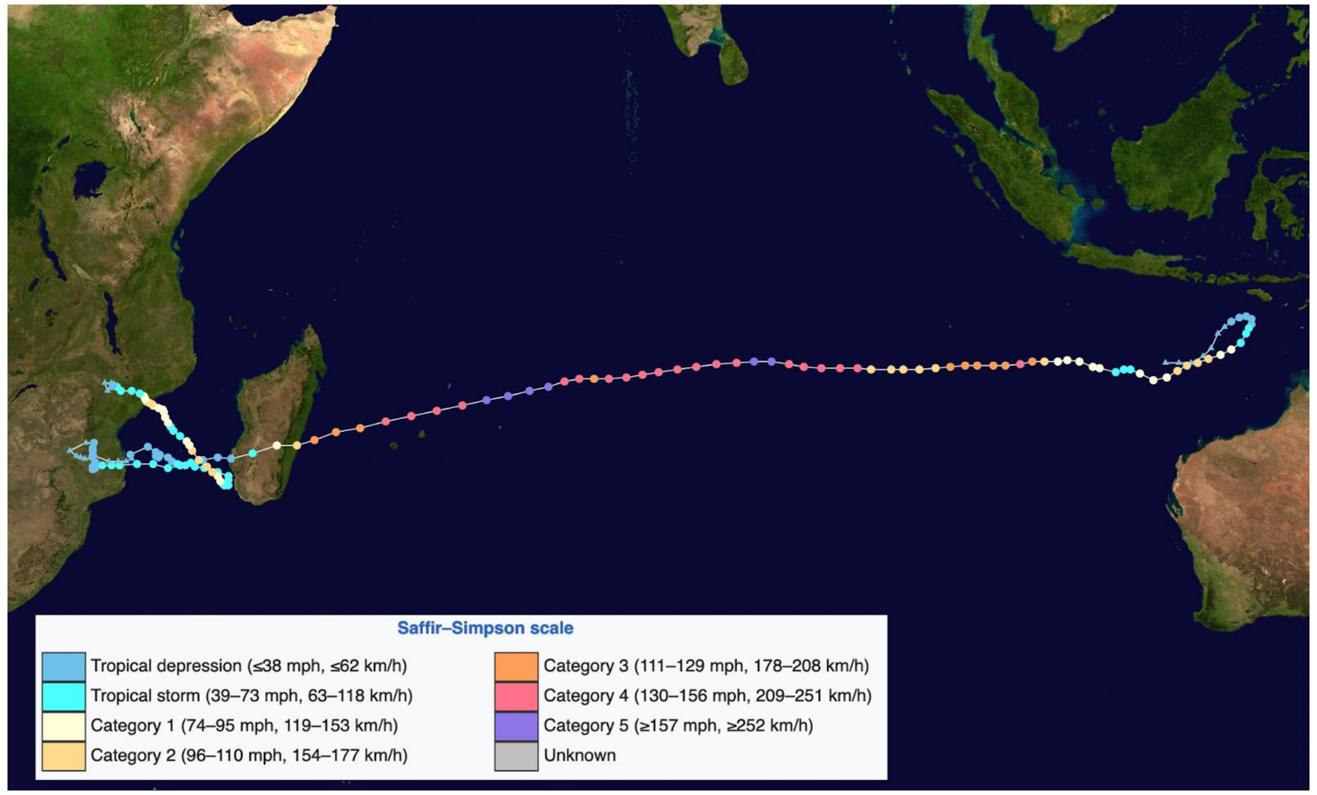
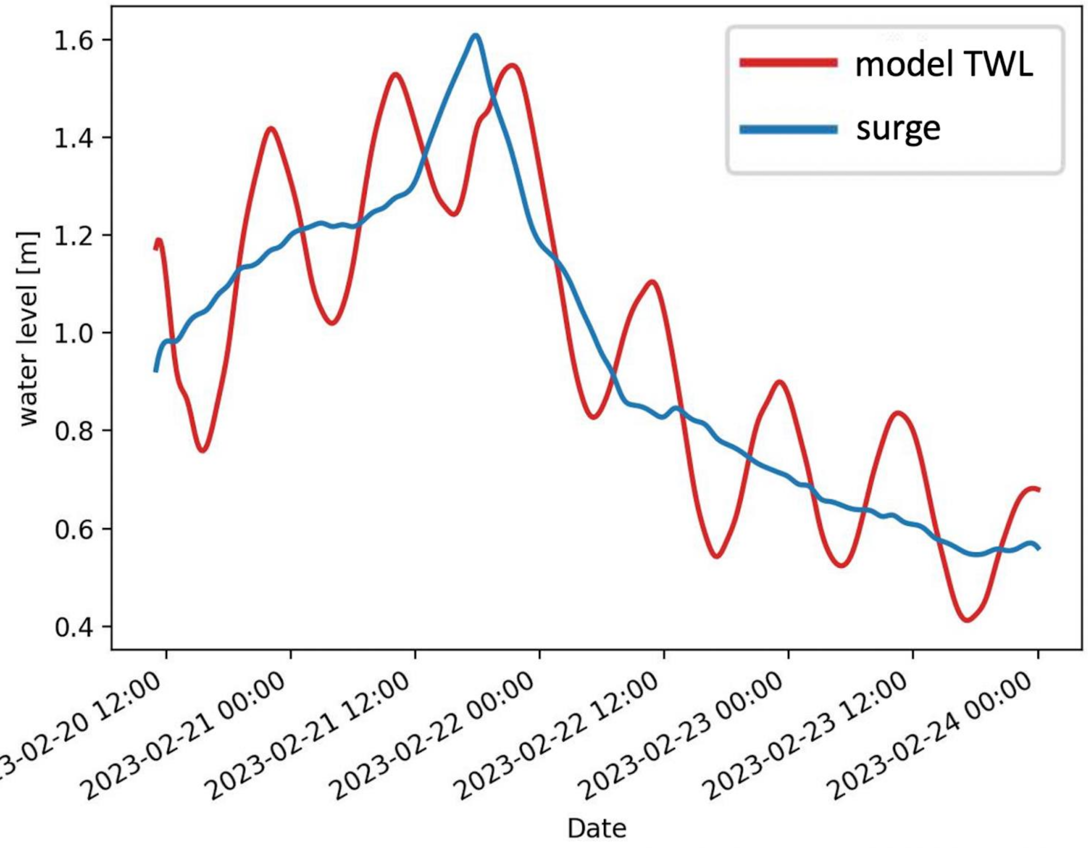
The Cyclone Freddy (February 2023)



The Cyclone Freddy track and intensity, according to the Saffir–Simpson, as reported by WikiProject Tropical cyclones/Tracks based on NRL and NOAA data.

- Cyclone Freddy first developed as a disturbance on 5 February 2023.
- While in the Australian region cyclone basin, the storm quickly intensified and became a Category 4 severe tropical cyclone, before it moved into the South-West Indian Ocean basin, where it intensified further.
- The JTWC estimated 1-minute sustained winds of 270 km/h (165 mph) at Freddy's peak strength, equivalent to Category 5 strength on the Saffir–Simpson scale.
- On 21 February, Freddy made its first landfall near Mananjary, in Madagascar. Then the storm rapidly weakened overland but re-strengthened in the Mozambique Channel.



The highest surge of the coastal scale of Mananjary occurred on 21 February at 18:00 with a peak of 1.6m, where we also include the total water level. The timing of the surge peak occurred with the ascending phase between ebb and high tides.

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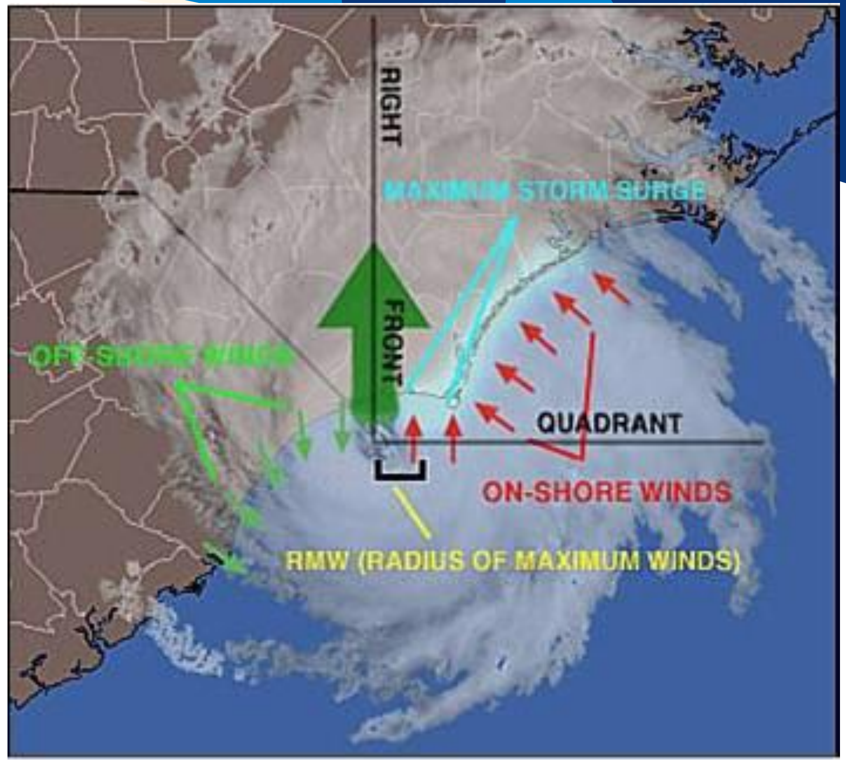
What causes the storm surge?

In general, storm surge occurs where ***winds are blowing onshore.***

The highest surge tends to occur near the "radius of the maximum winds" --where the strongest winds of the hurricane occur.



Storm Intensity

Stronger winds will produce a higher surge.

Width and Slope of the Ocean Bottom

Higher storm surge occurs with wide, gently sloping bottom with narrow, steeply sloping shelves (bottom).

Approaching angle

The angle at which a storm approaches a coastline can affect how much surge is generated.

Shape of coastline

Storm surge will be higher when a hurricane makes landfall on a concave coastline

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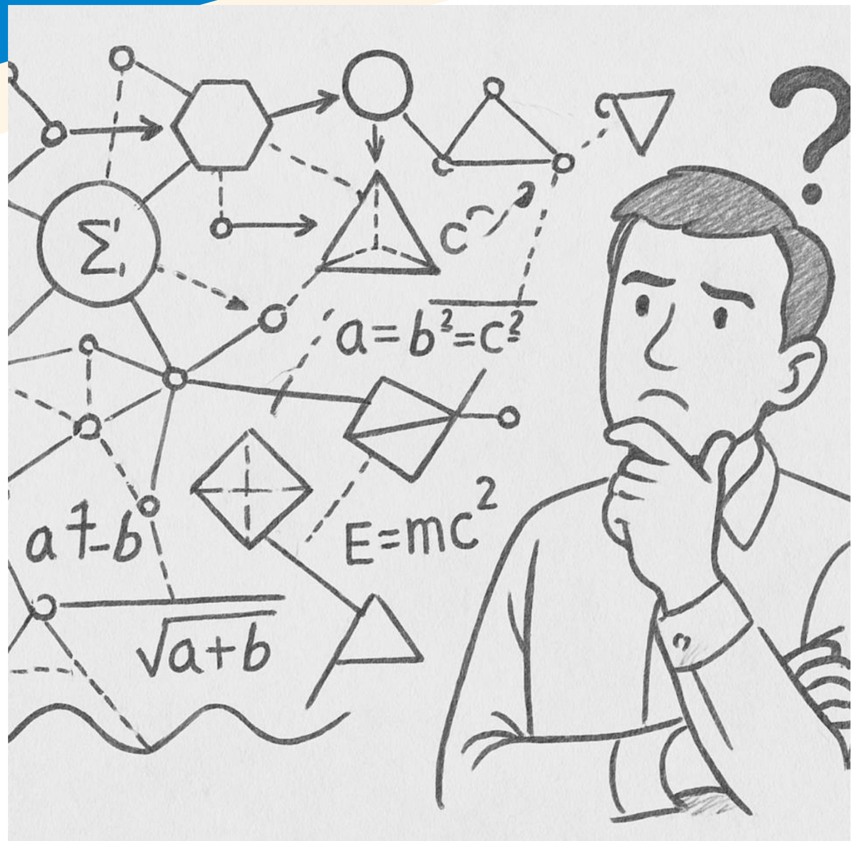
How much complex is the system ?



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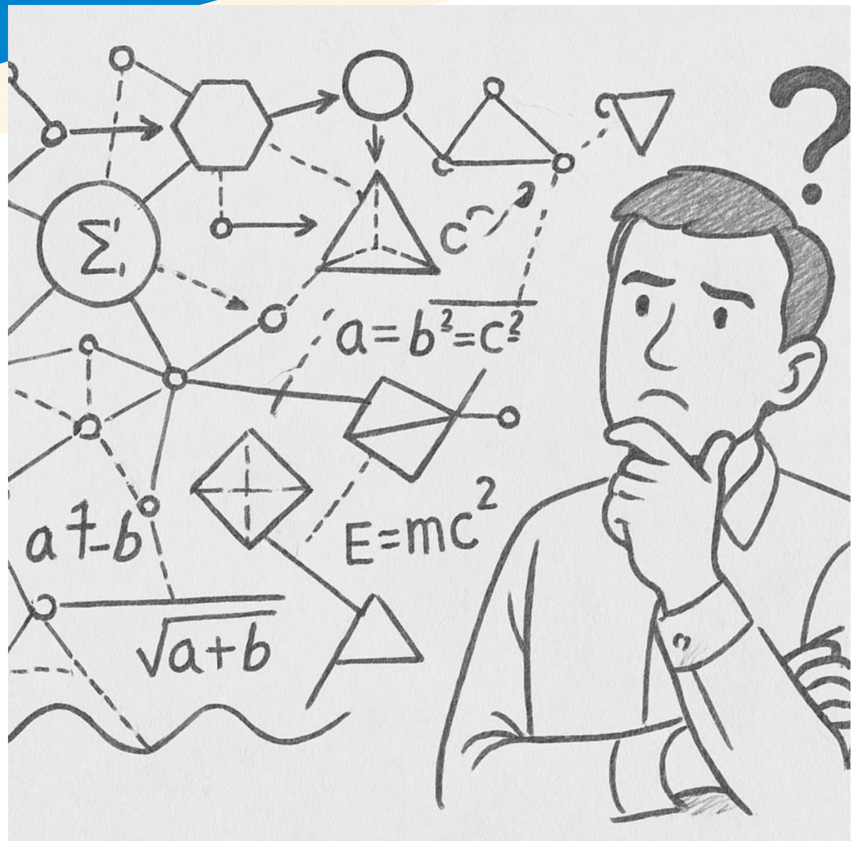
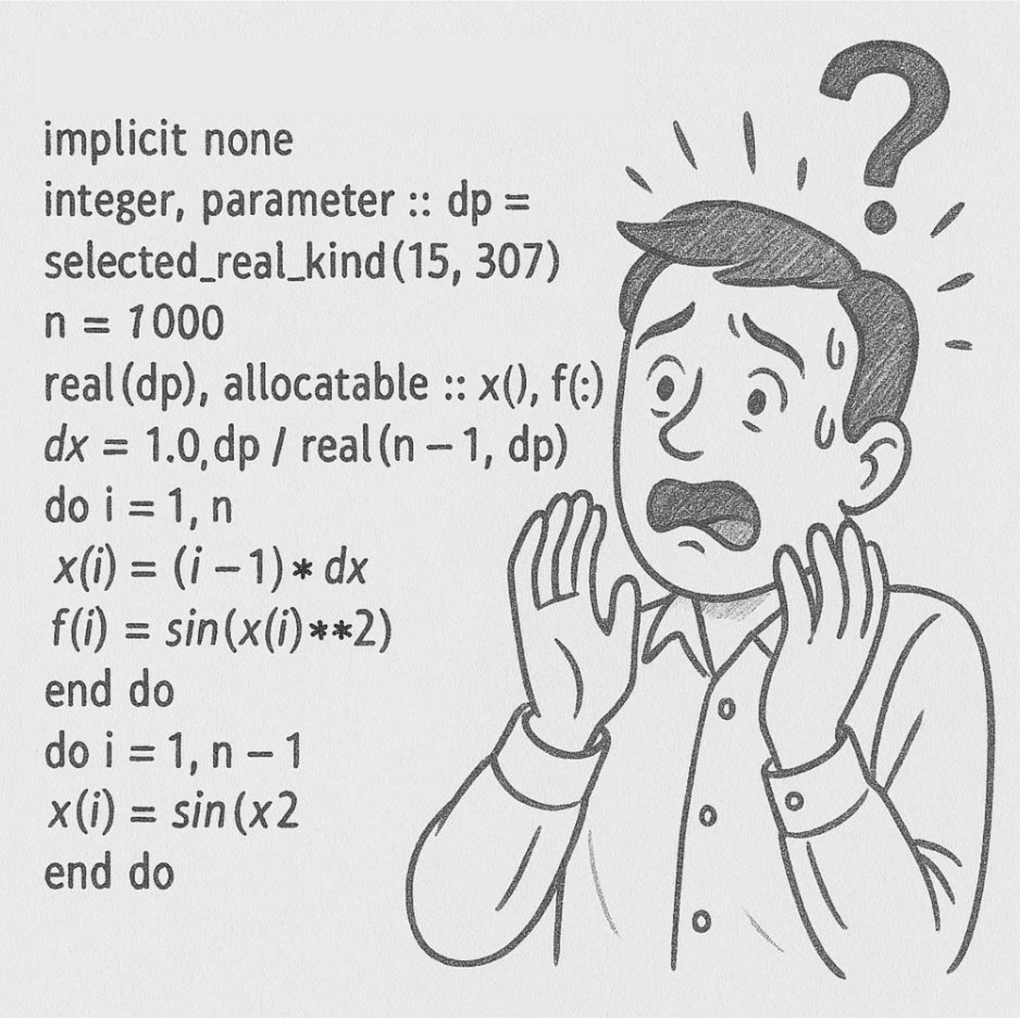


How much complex are the numerical models?



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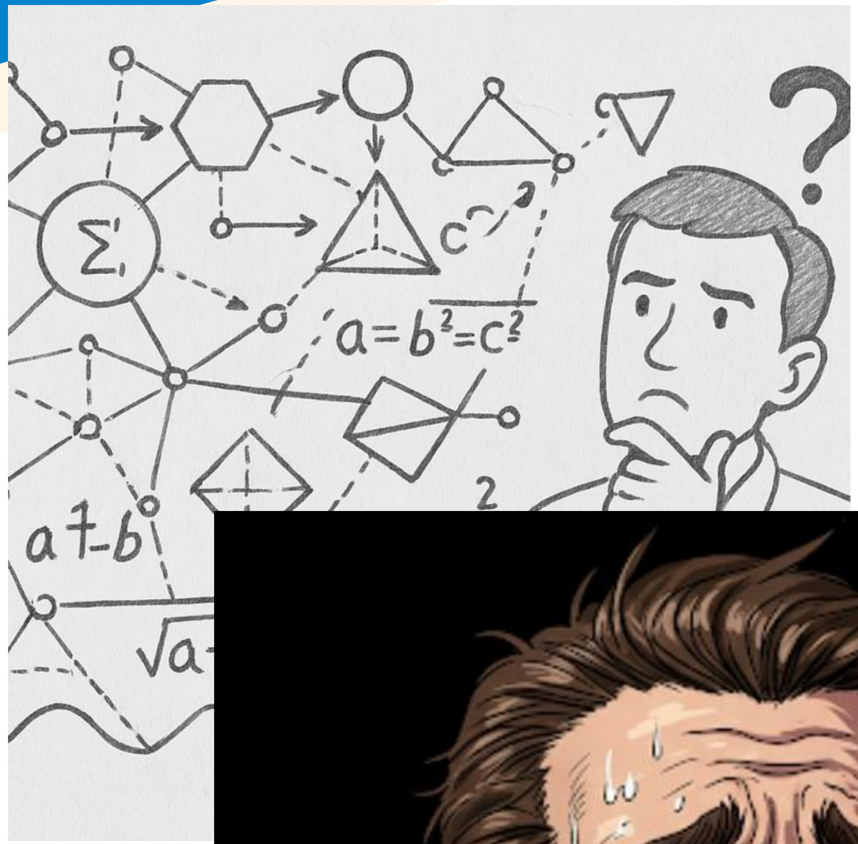

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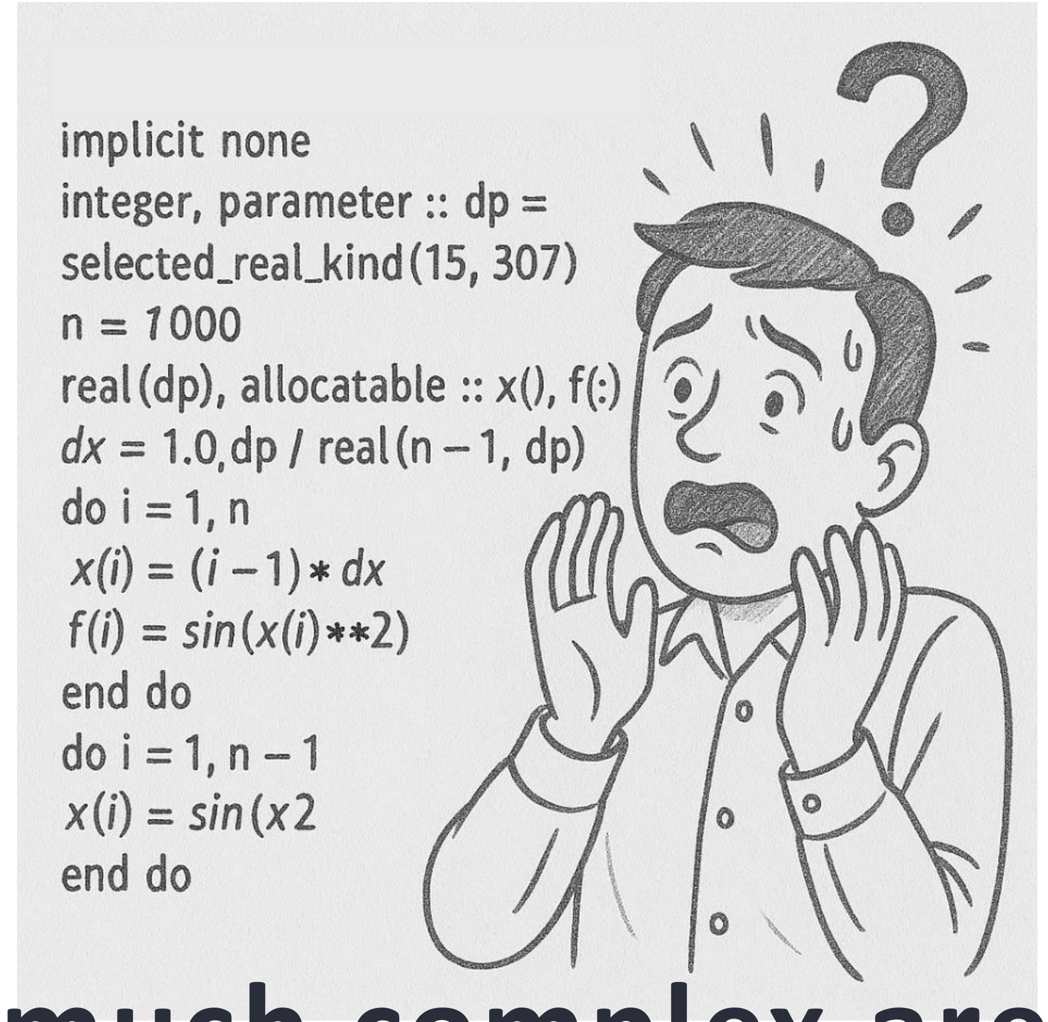

How much complex are hazards and their relations?

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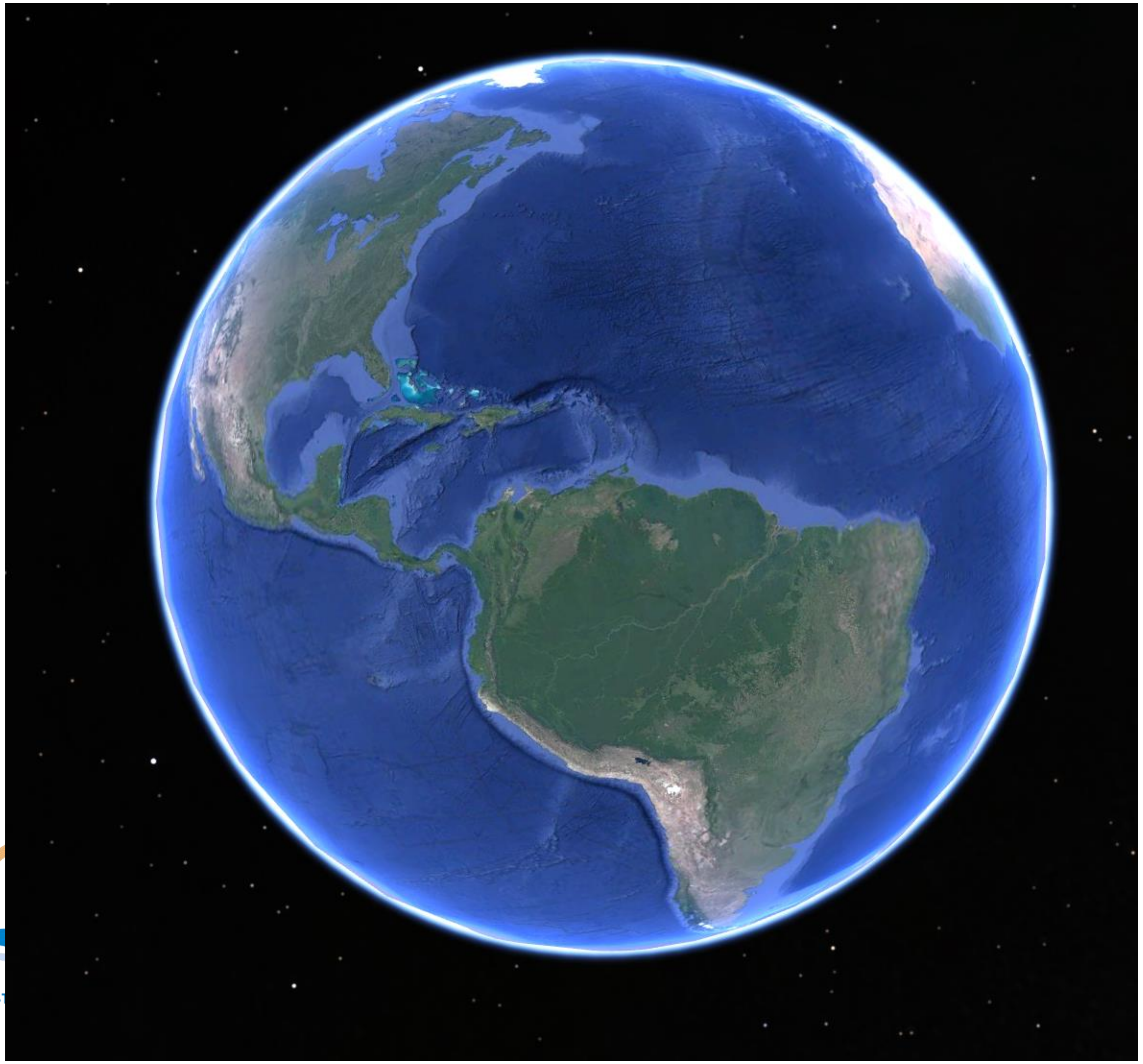
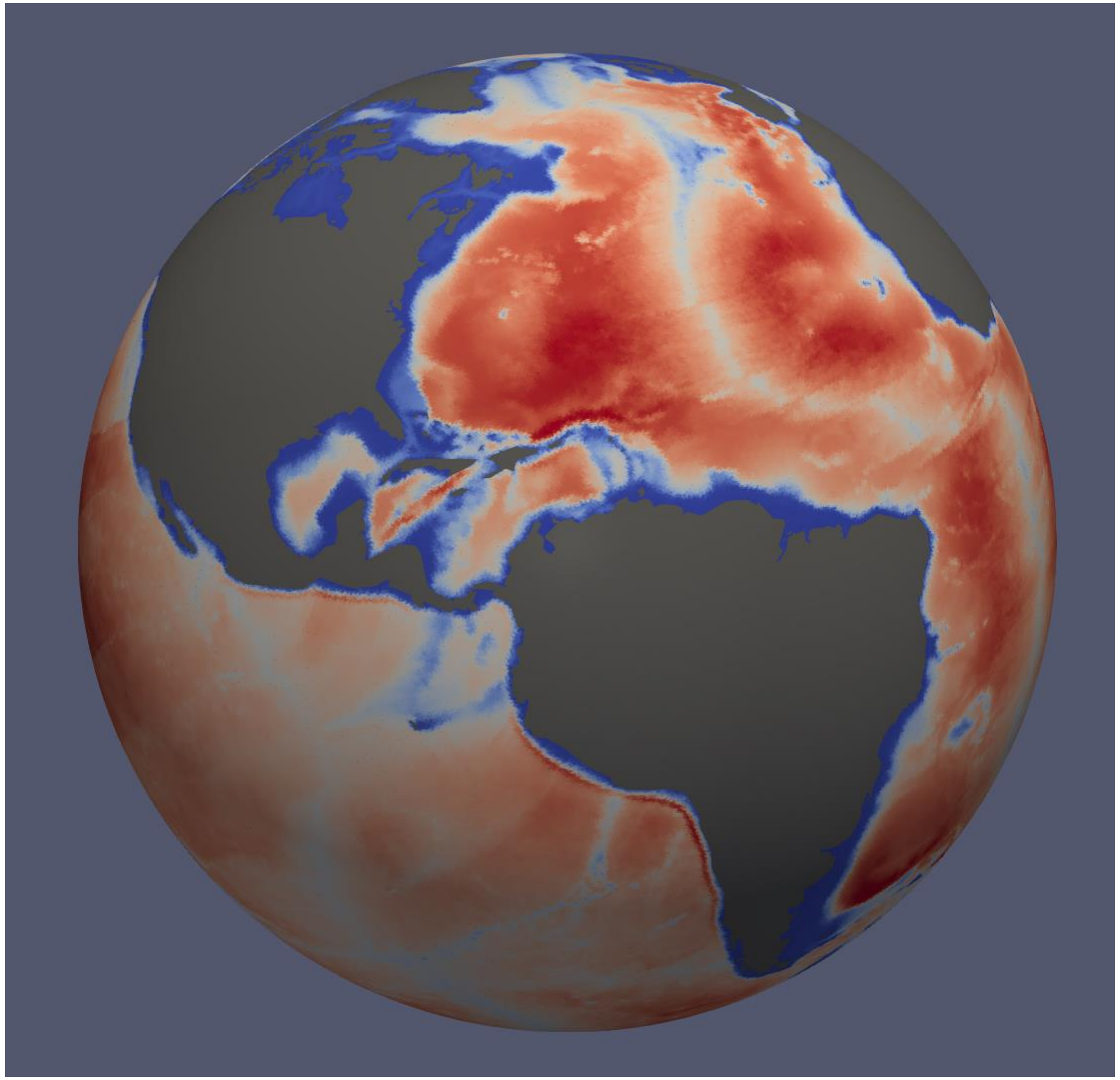
- Complex processes to understand /describe/simulate
- Knowledge in numerics and programming language
- Required data from observation and models to feed my equations
- Computer facilities
- Proper representation of the results and their interpretation

The Digital Twin of the Ocean…

$$\begin{pmatrix}\text{digital}\\ \cancel{\text{virtual}}\end{pmatrix}\begin{pmatrix}\text{representation}\\ \cancel{\text{copy}}\\ \cancel{\text{clone}}\end{pmatrix}\text{ of }\begin{pmatrix}\text{(physical) reality}\\ \cancel{\text{an object}}\end{pmatrix}\text{ using }\begin{pmatrix}\text{models}\\ \text{data}\end{pmatrix}$$





COAST

The Coastal Digital Twin of the Ocean…

Integrated multi-physics approach tailored to coastal and nearshore scales **real-time short-term forecasts and hindcasts**

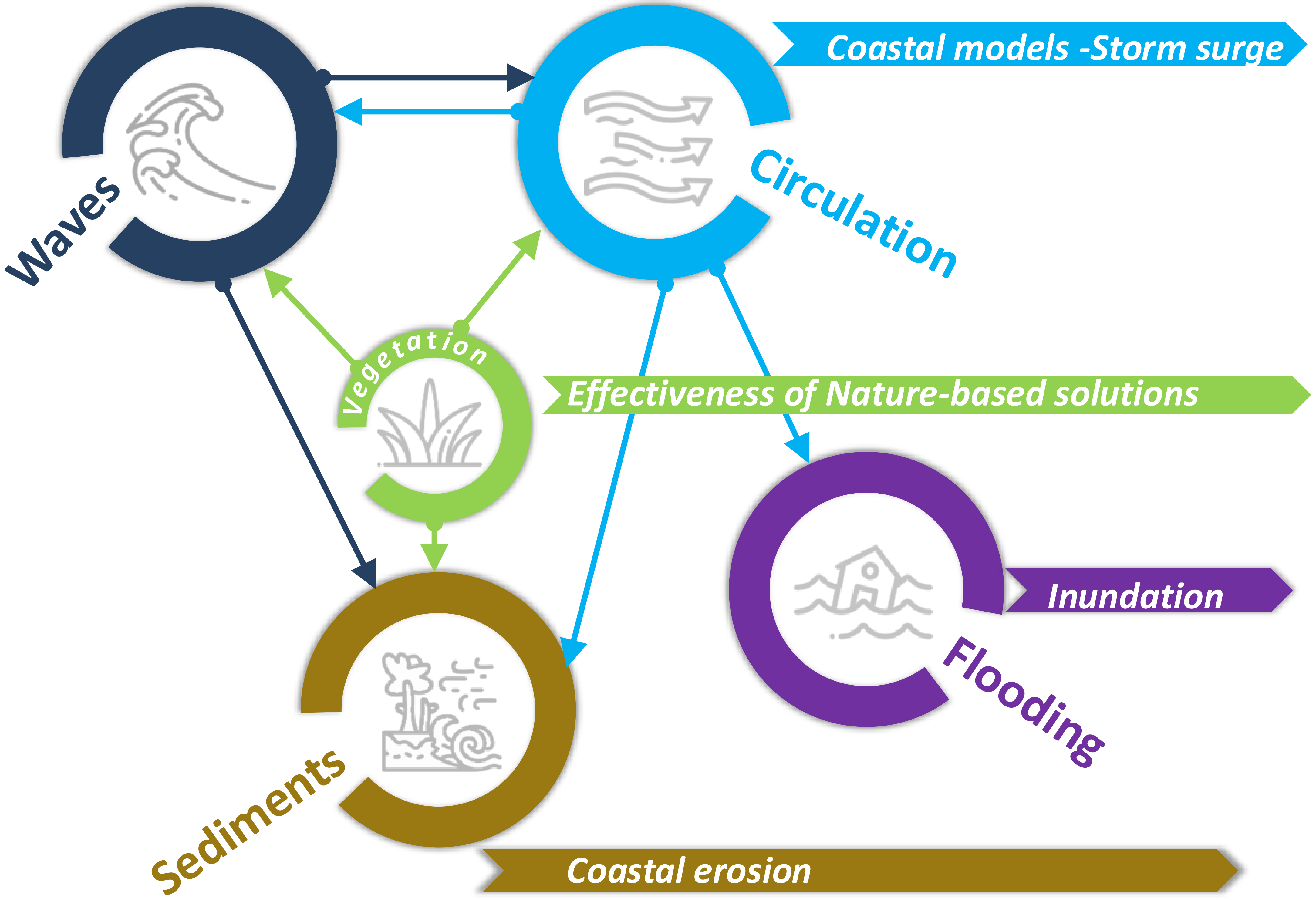
Combining **modeling** and **observational data,** and elements of **AI**

Designed for **end-user usability**

"What-if" scenarios

Capacity for **relocability**

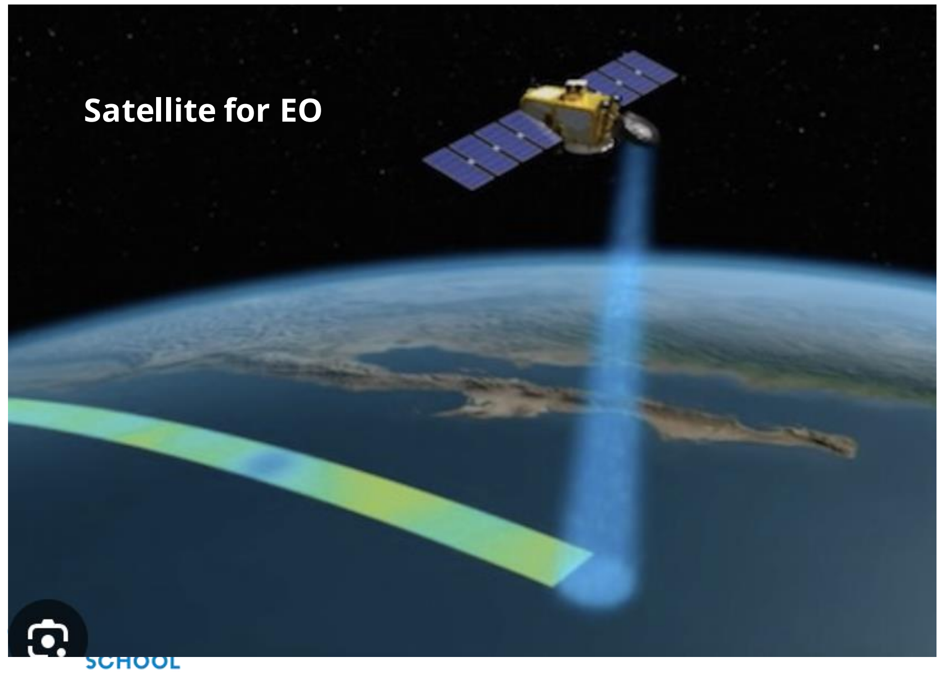
Improved use of **computational resources**

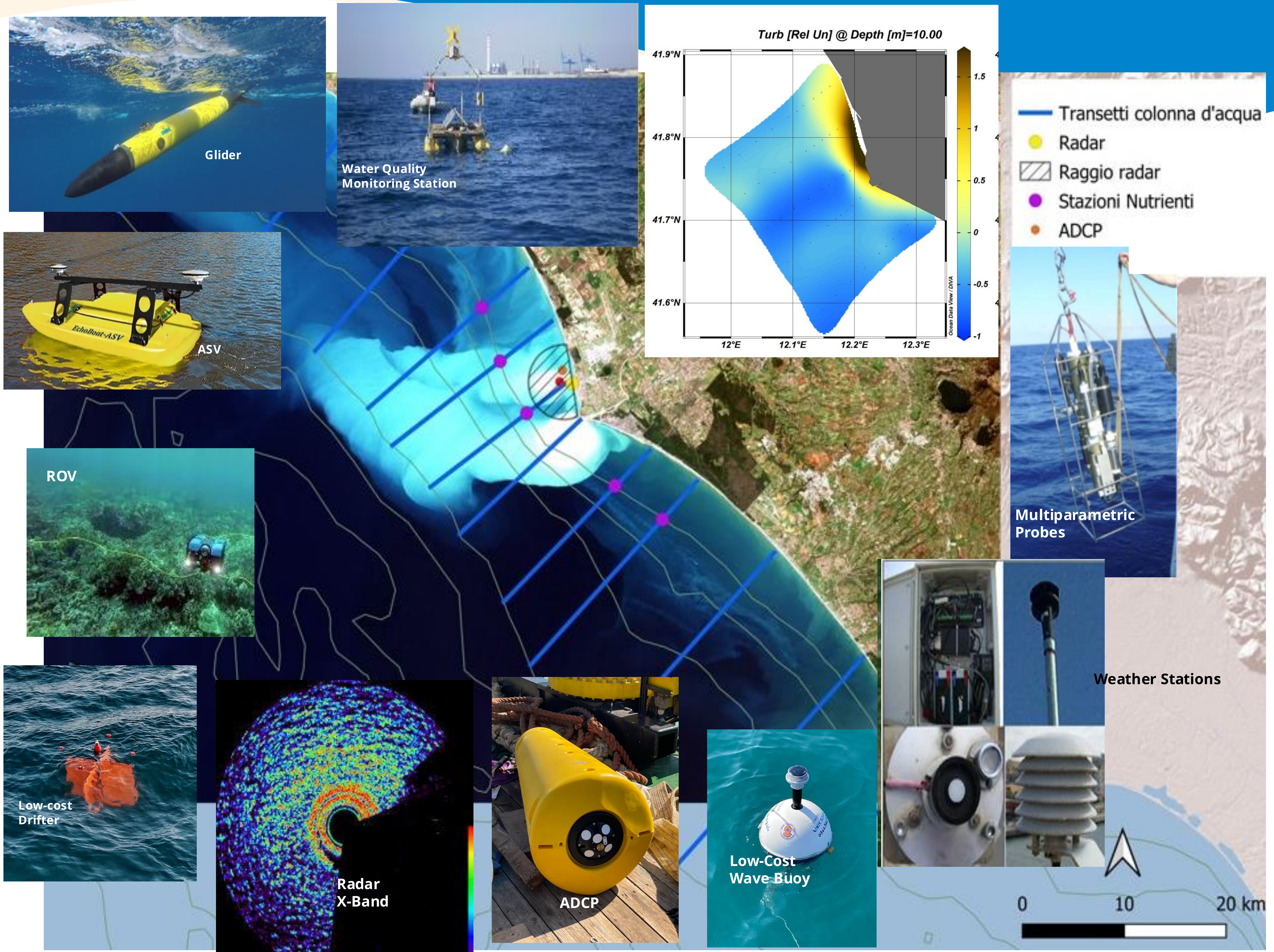


Observations

Extremely important:
- Data assimilation
- Validation

Sparse in time and space





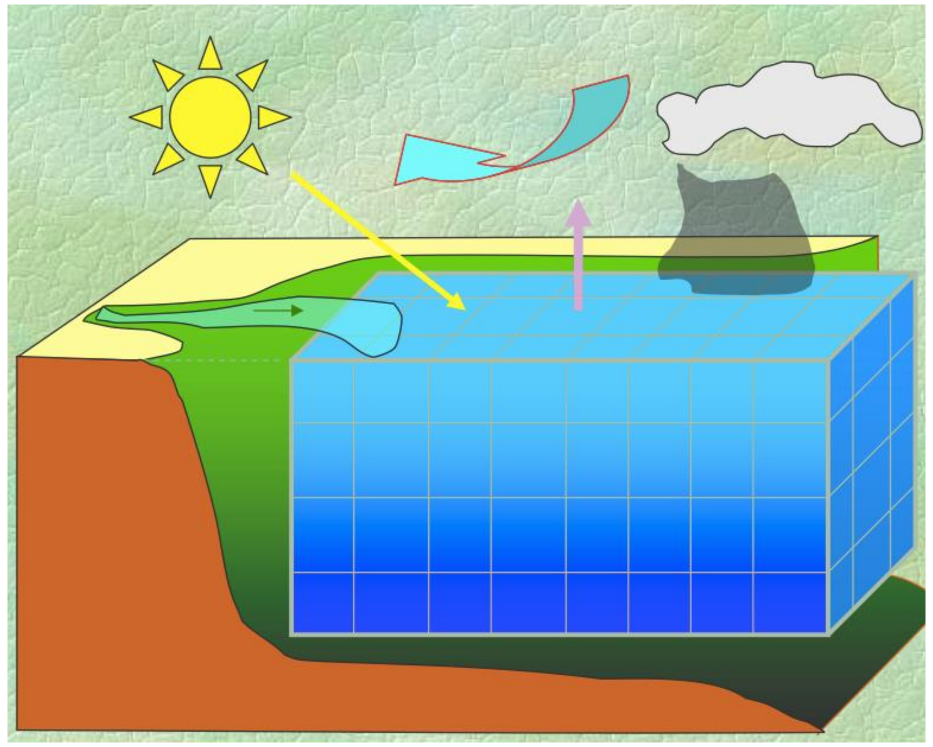
Numerical models for processes study, extremes and operational forecasting

The **limited area** modelling approach is based on **DOWNSCALING** of **unstructured grids,** which have the advantages to set a **multi-resolution** in the same domain in a **seamless** fashion

3D FEM circulation model: SHYFEM-MPI

Two-way coupling

Spectral Wave model: WW3



Computational grid: the equation are discretised in each cell considering the contribution of the surrounding cells

- Initial conditions
- Surface boundary conditions
- Lateral open boundary conditions
- Climatologies and rivers

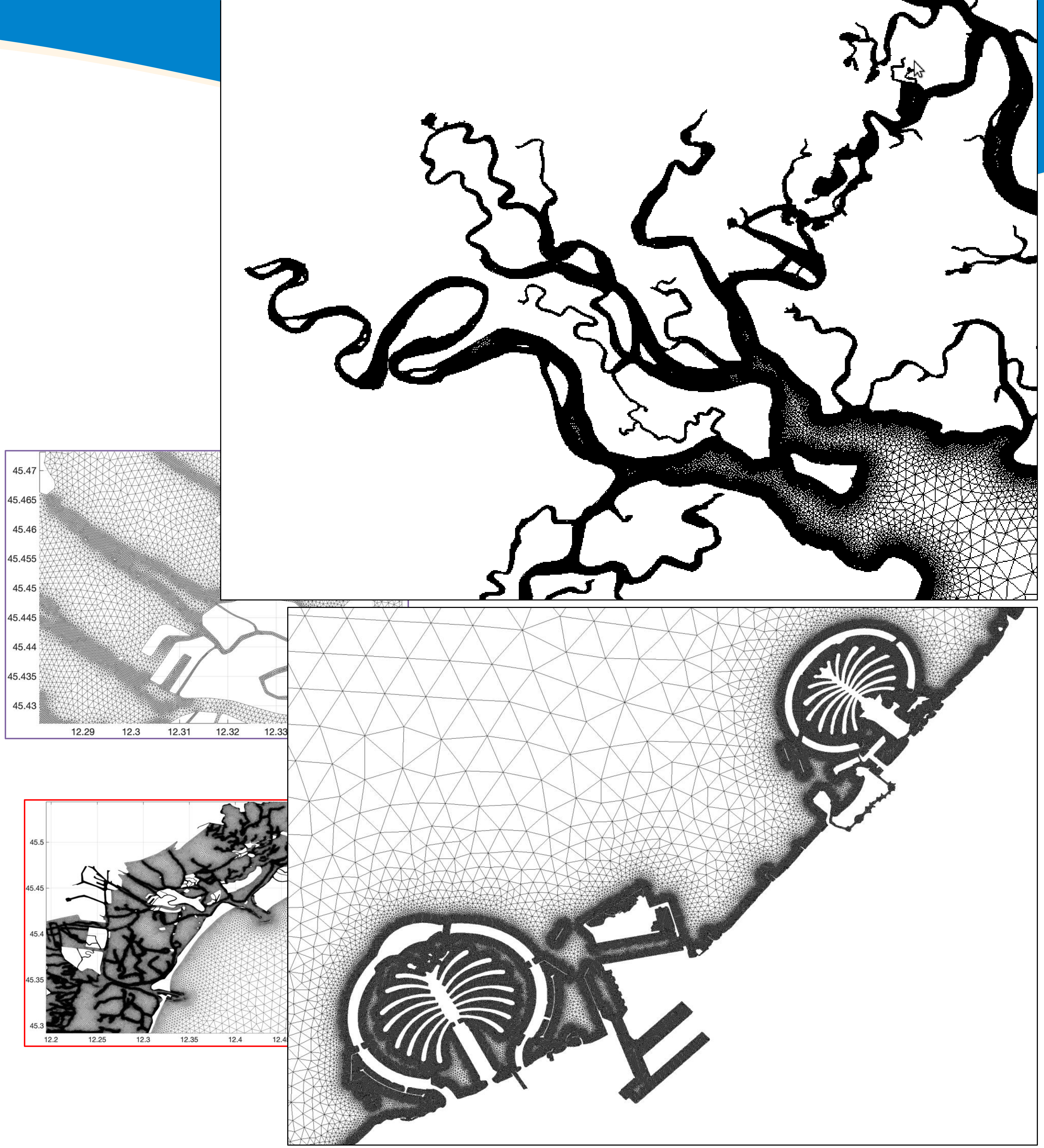
WHY unstructured grids

1. Traditional <u>downscaling process: </u>multiple-nested domains, required boundary conditions provided by a coarser model

2. Unstructured grid: single grid with SEAMLESS increase of resolution in target areas (coasts). No or minimal nesting procedures.

3. More accuracy in coastline geometry

4. Intrinsic two-way nesting: information is transferred from the coarser to the finer domain and vice versa



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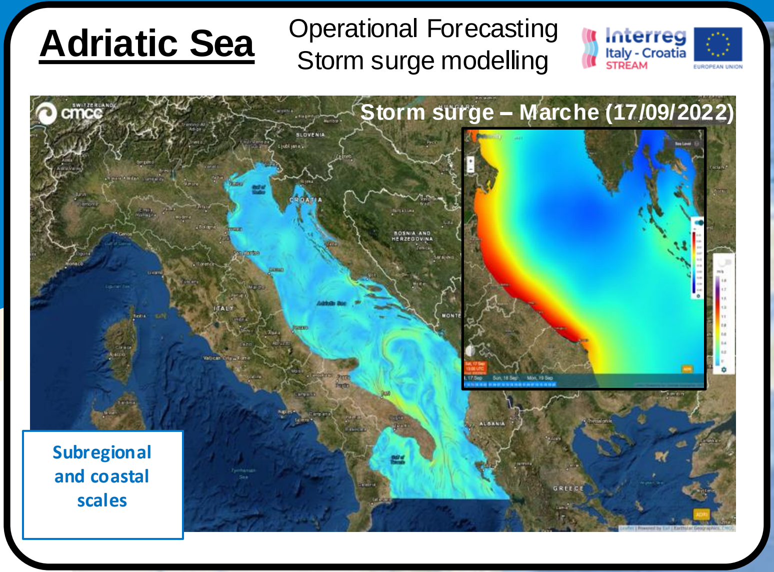
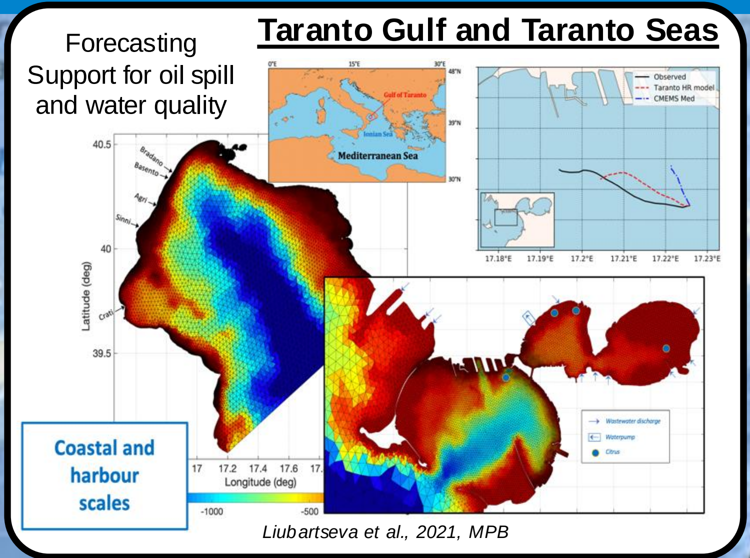
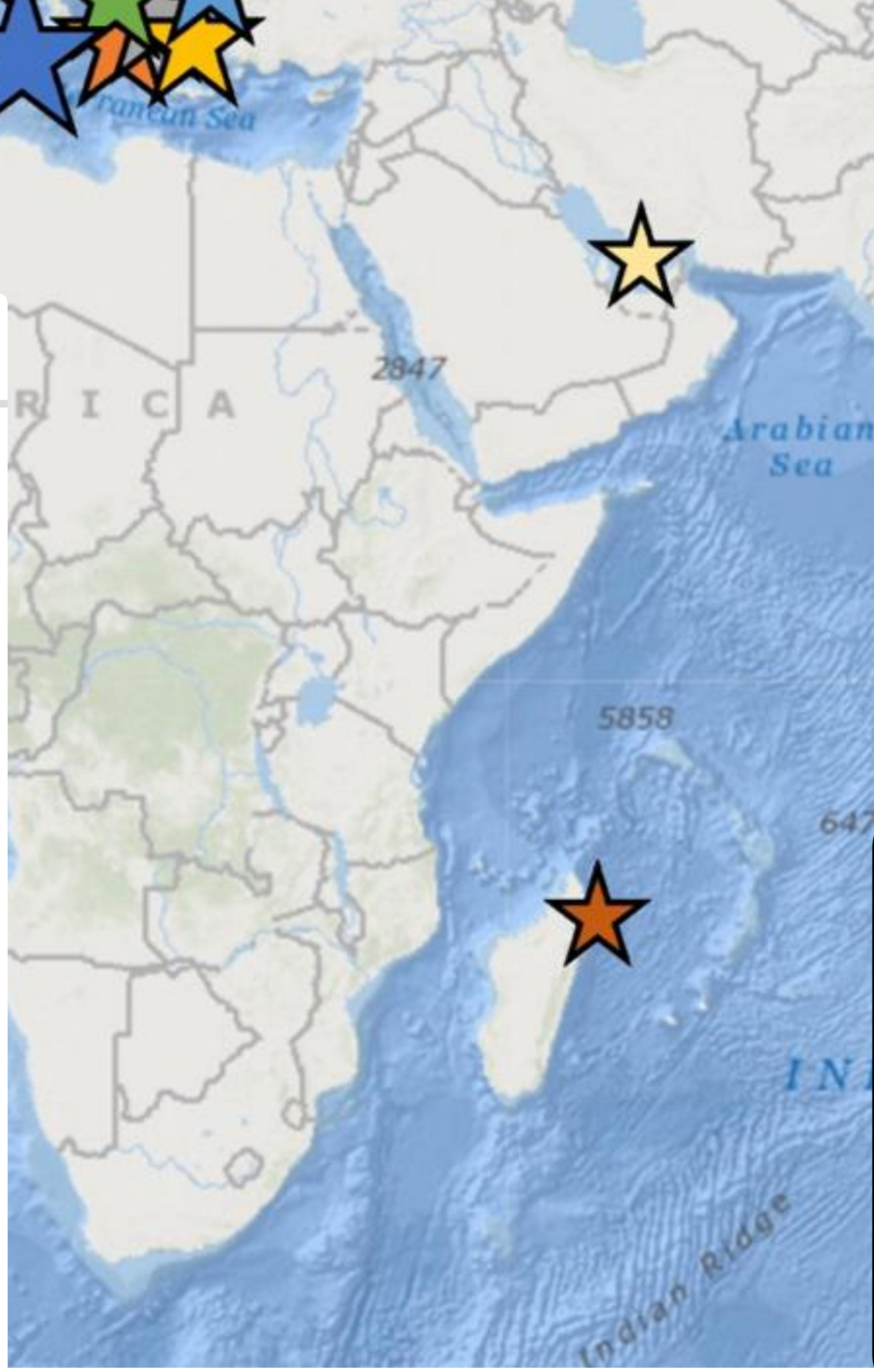
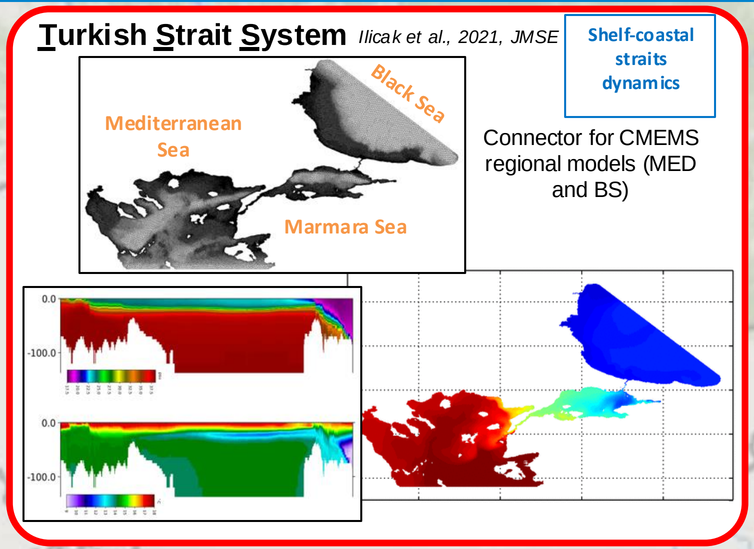
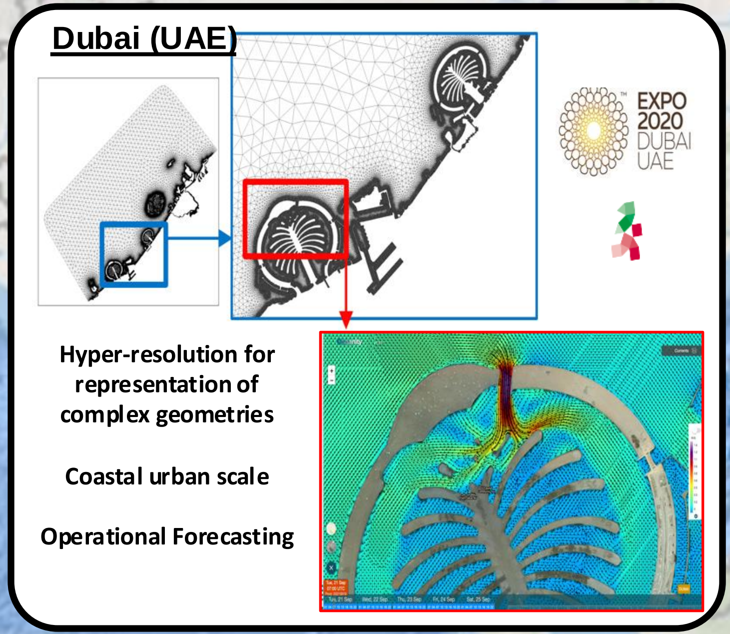
"BUT CREATING THEM IS COMPLEX"

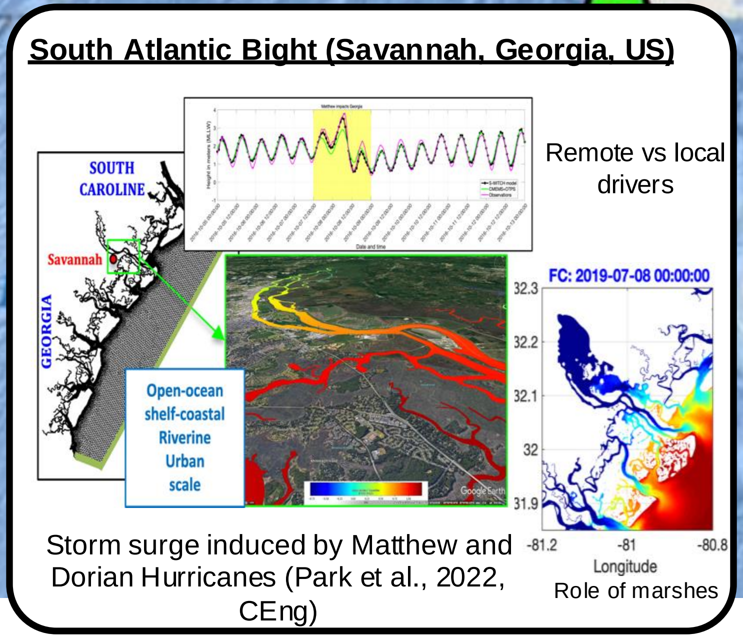












Downscaled coastal models

30+ implementation over the world

Easy deploy and relocability

Cross-scale Operational forecasting or hindcast for event-based approach

Port and oil-spill applications

Strait dynamics

Urban ocean

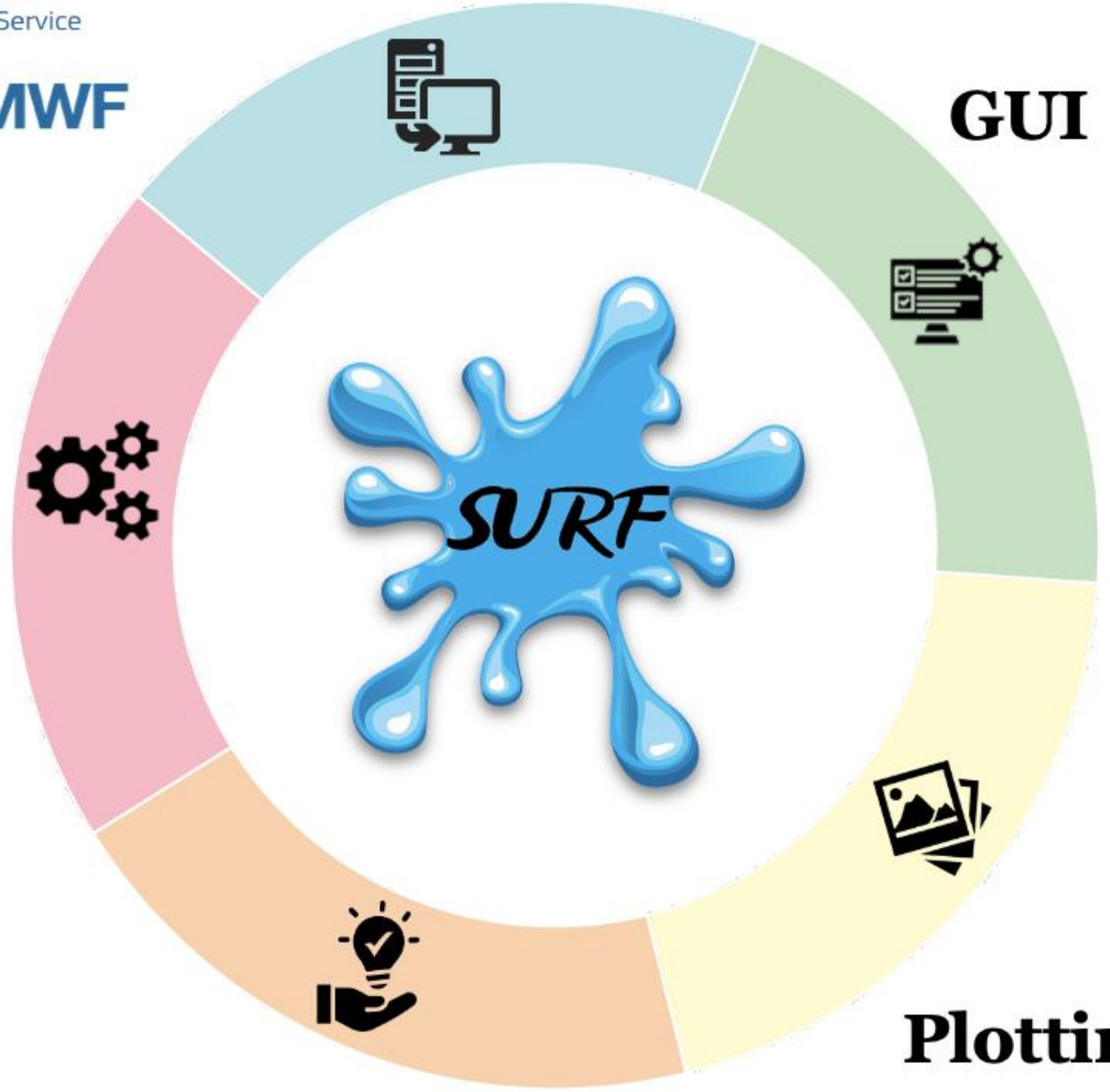
Storm surge

The solution: SURF, an on-demand ocean forecast platform

Automatic data download

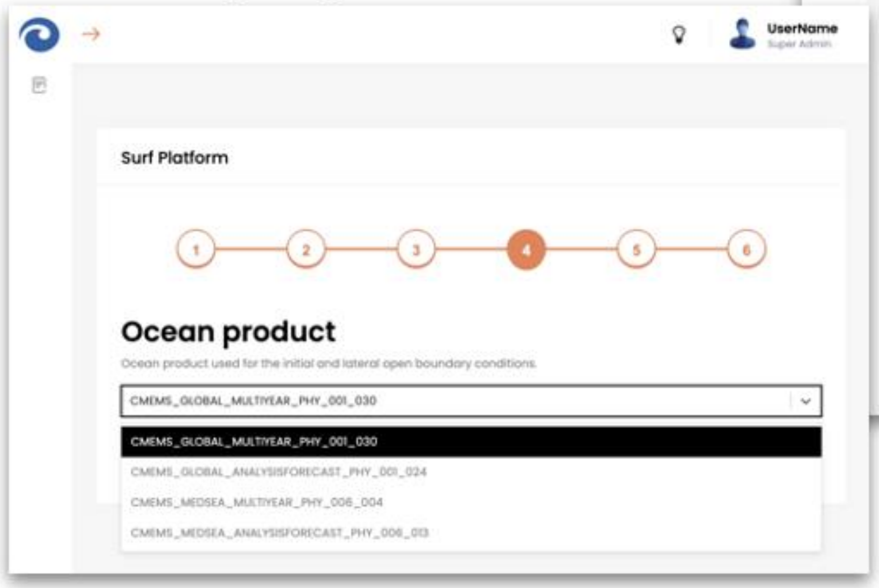
Copernicus Marine Service

ECMWF

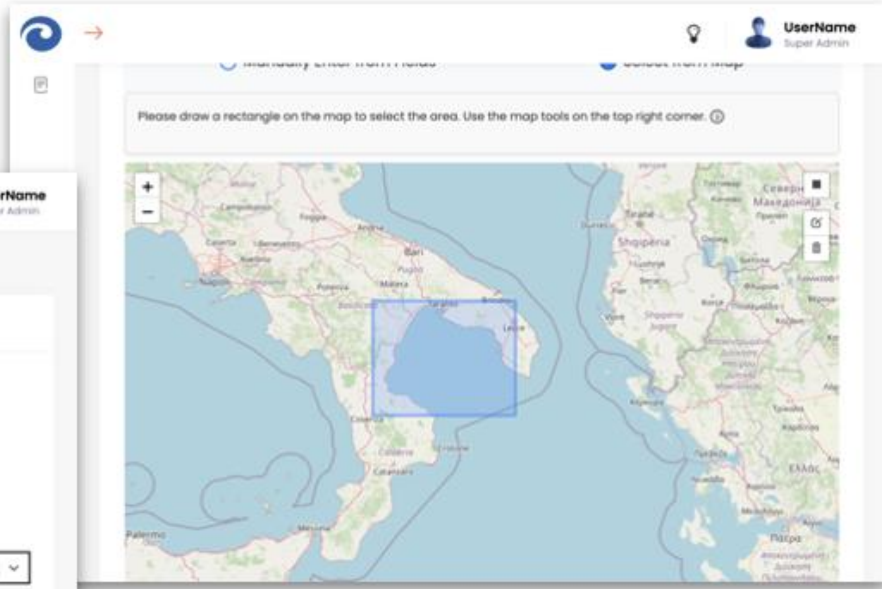


GUI

Input products choice



Graphical domain selection

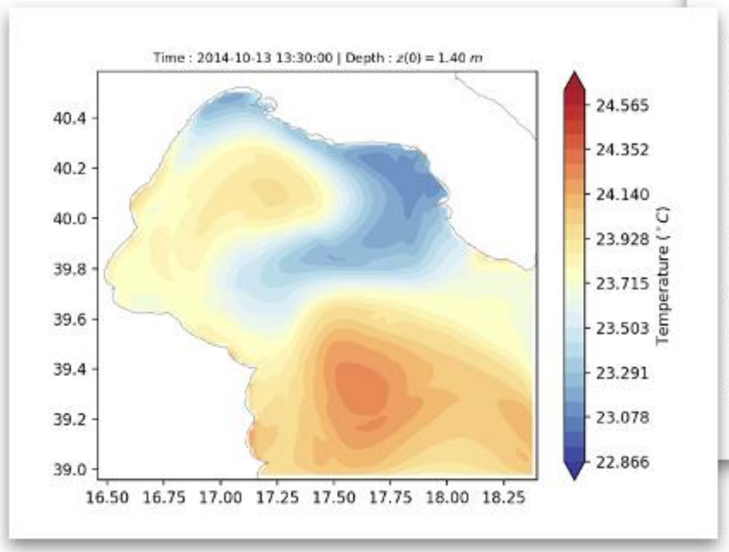


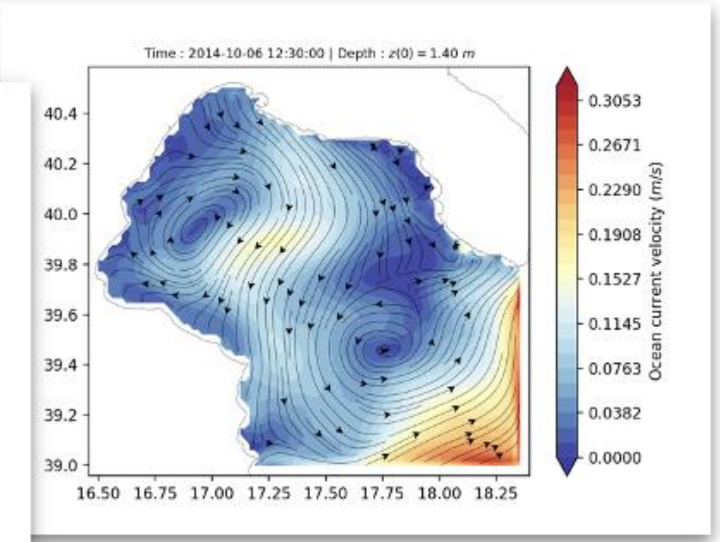
Precompiled models

NEMO v5.0β

SHYFEM-MPI

Plotting

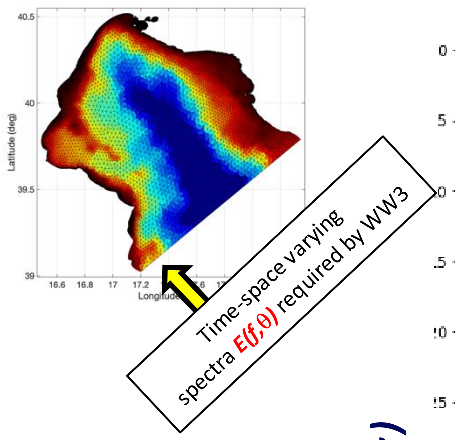


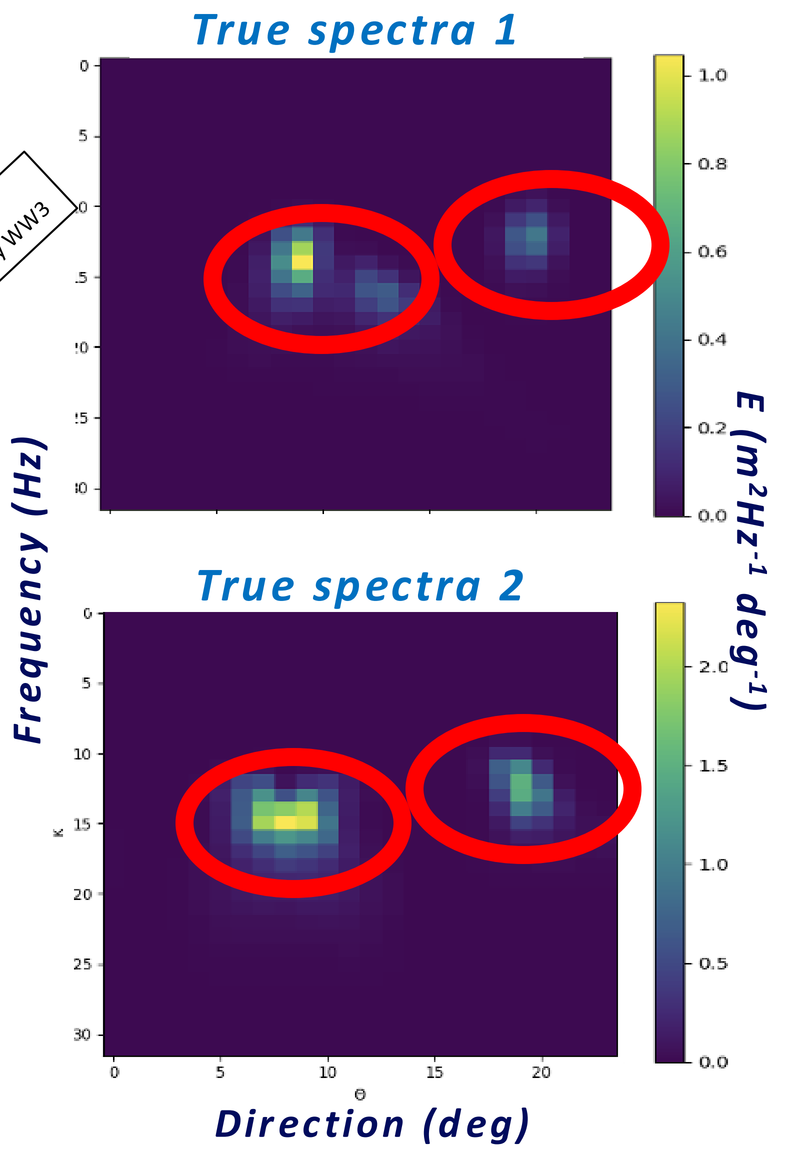


Preconfigured simulation
(≳95% params set to default)

Example of AI contribution: improving downscaling

Deep Learning-generated energy spectra, streamlining downscaled **wave models**



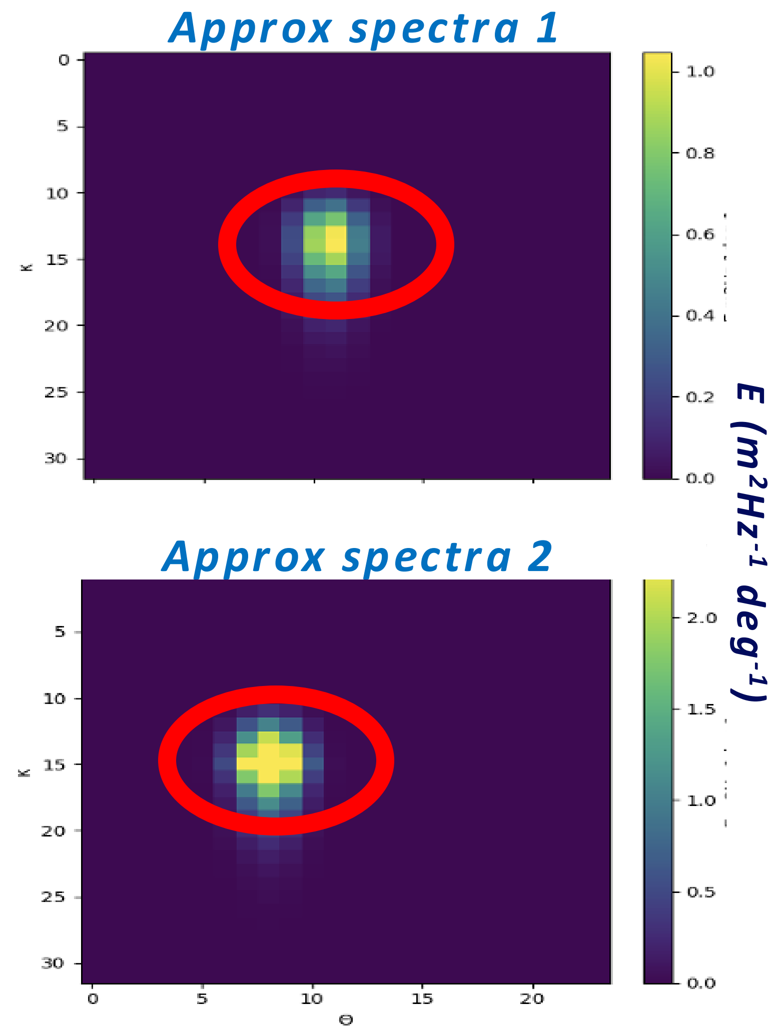


Real spectra

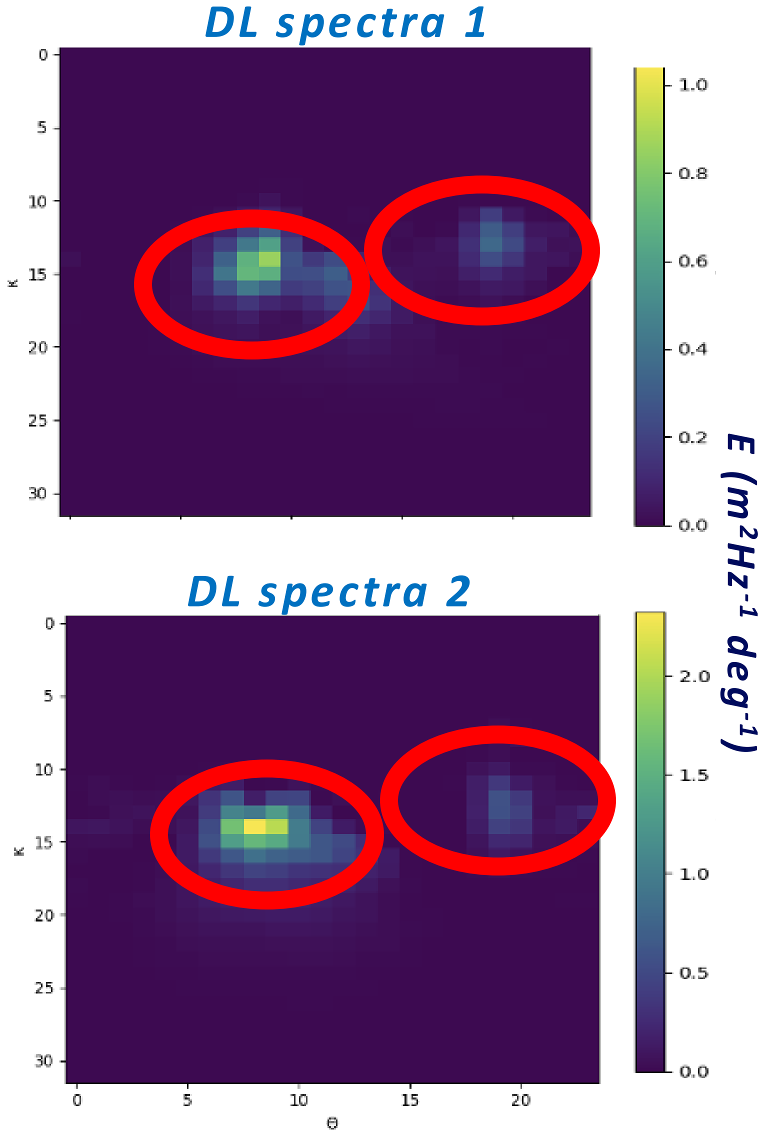
Wave model need wave energy spectra at the open lateral boundary.
High-storage cost, very low availability

Traditional solution

Consolidated approach in approximating the spectra by using standard mean parameters as SWH, WPP, MWR



Good approximations for zeroth and firsts moments, not able in reproducing multipartition spectra

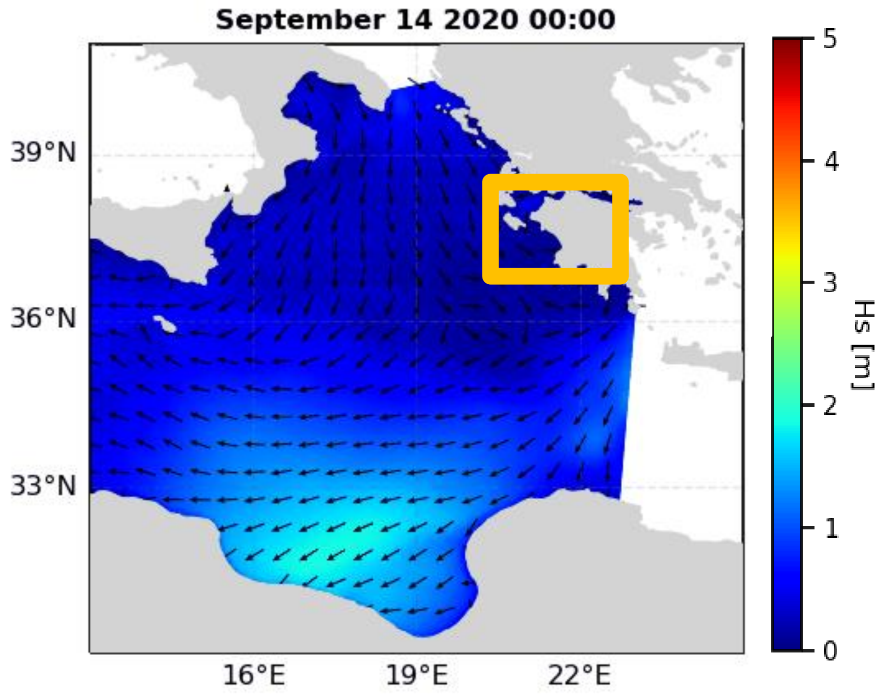


Innovative and integrated solution

Exploitation of DL in approximation of spectra could improve the representation of multipartition spectra

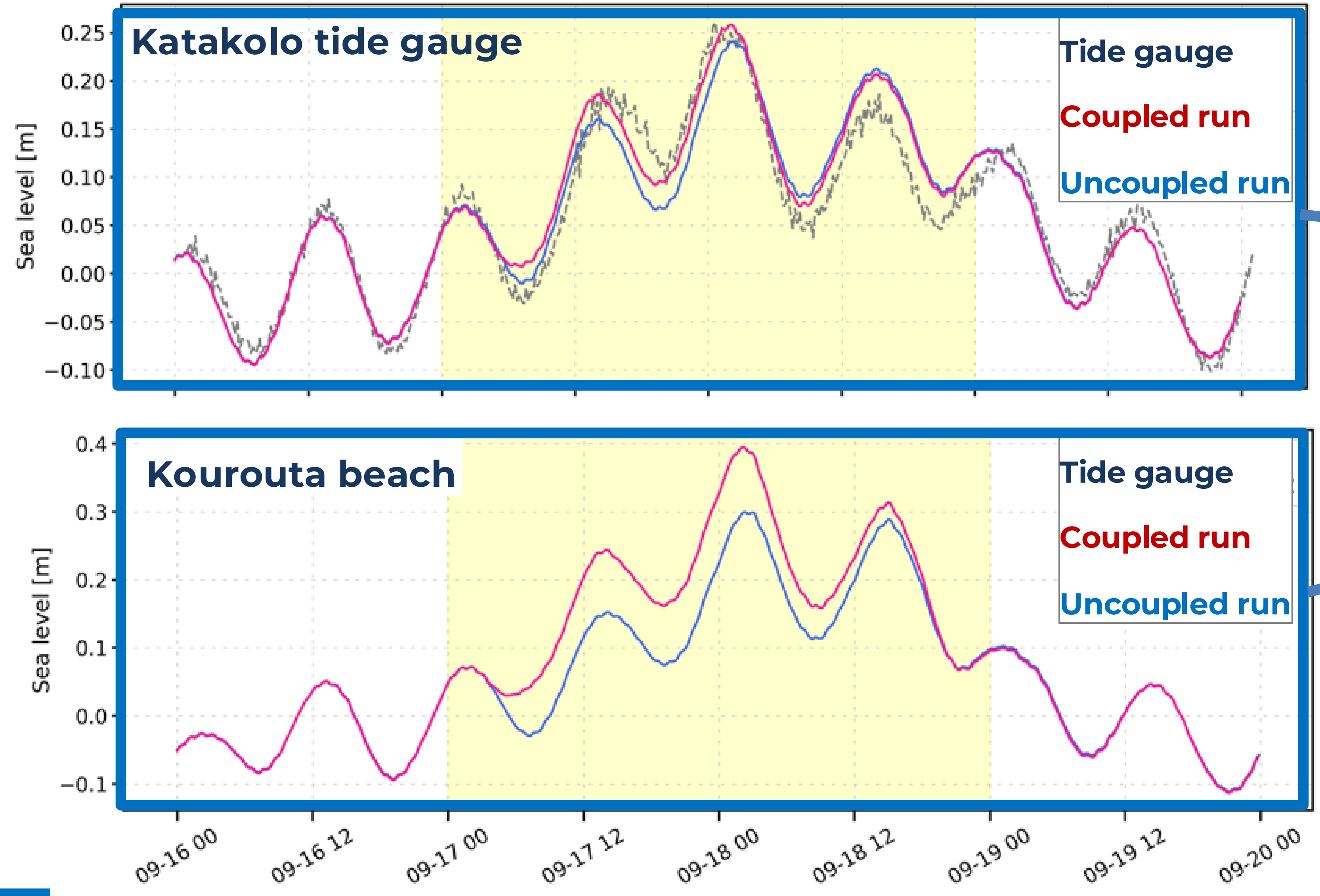
Storm surge: wave-currents interaction

Storm surge modelling based on *Longuet-Higgins, Stewart theory* and forecasting Mediterranean tropical-like cyclone



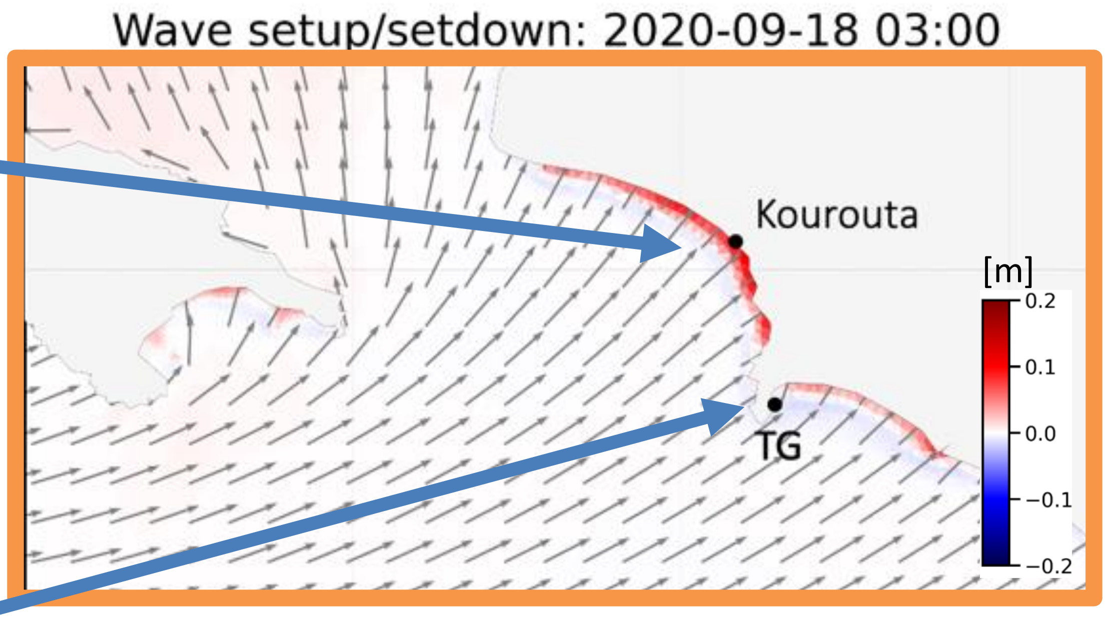
Medicane *Ianos*, 2020

One of the strongest storms recorded, in terms of duration and intensity. Caused winds gusts up to 110 Km/h, heavy rainfall, storm surge and **flooding**, **damages** and **fatalities**



Storm surge validation

Total water level for **coupled** and **free run** are compared with Katakolo **tide gauge** -TG (gray). Coupling improved the the model accuracy in describing the event.
In the bottom panel, the model configurations are compared at the Kourouta beach.



Wave setup and setdown

TWL difference between free and coupled runs. Vectors show the mean wave direction. The variability of TWL, considering the wave contribution, could reach 30%.

Causio, S., Shirinov, S., Federico, I., De Cillis, G., Clementi, E., Mentaschi, L., and Coppini, G.: Coupling ocean currents and waves for seamless cross-scale modeling during Medicane Ianos, **EGUsphere**
https://doi.org/10.5194/egusphere-2024-3517, 2024.

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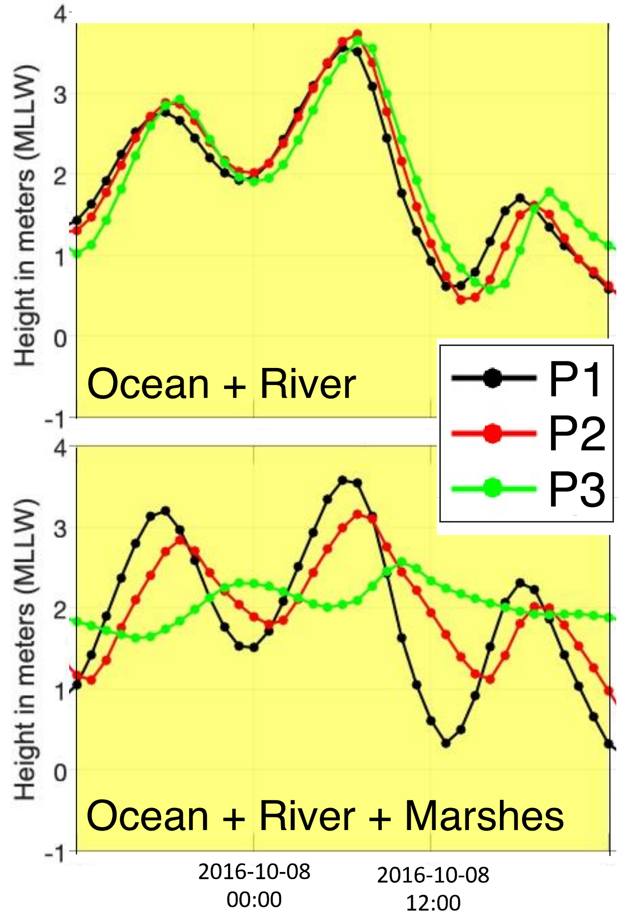
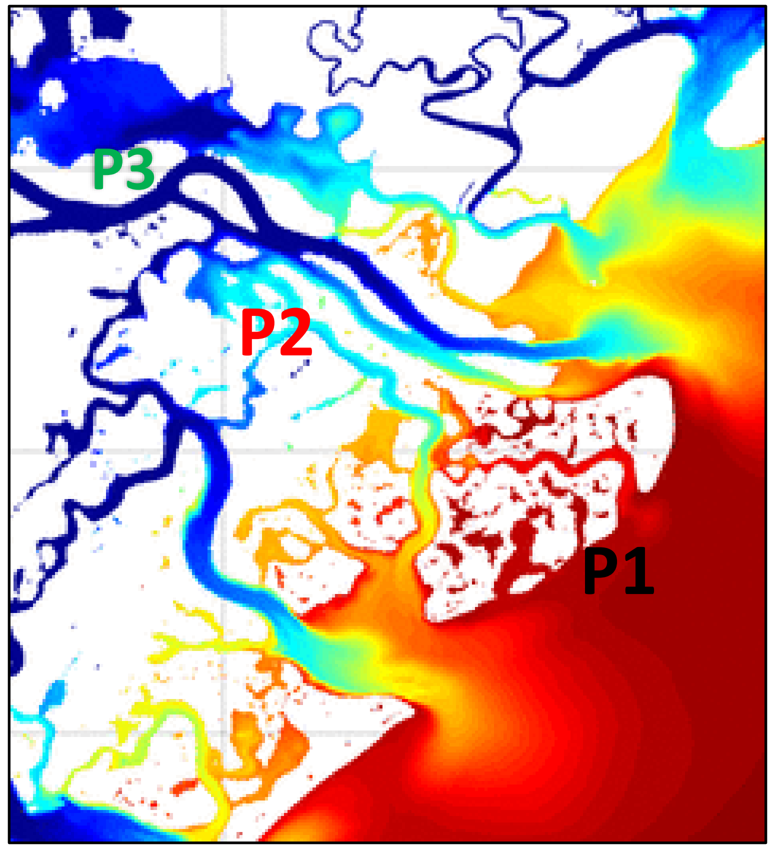
Flooding: downstream MODELS from circulation and WHAT-IF SCENARIOS

The methodology is based on different levels of complexity, ranging from simple Wet-&-Dry modules to models such as XBEACH and LISFLOOD-FP for simulating floods.

Hurricane *Matthew* impacts Georgia's coast

2016



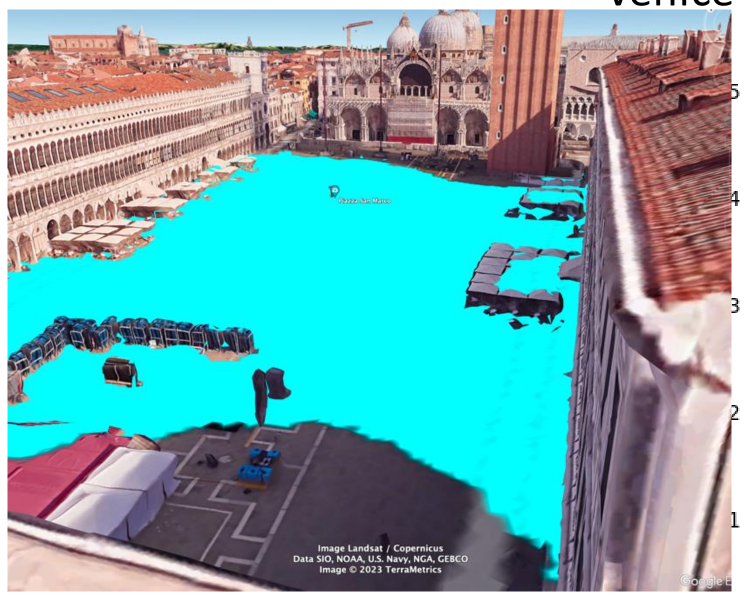


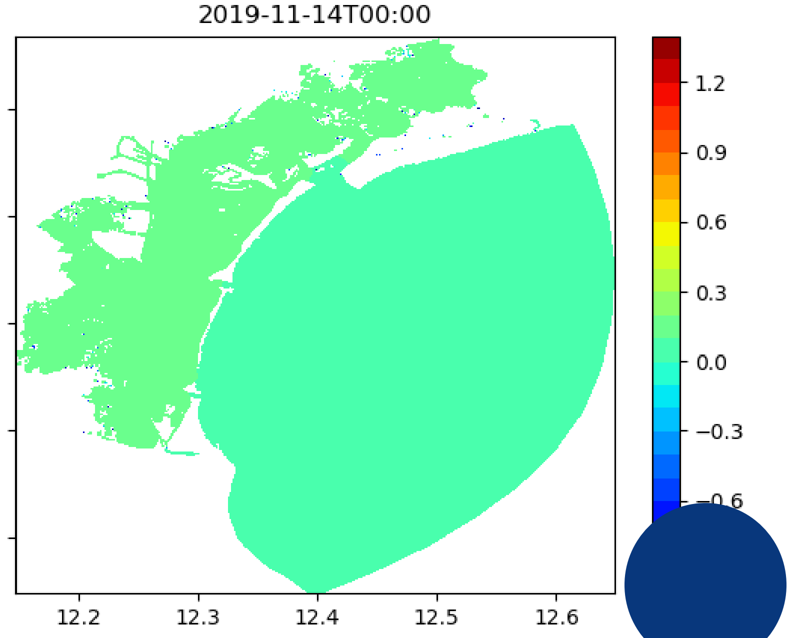
Characterization of **marshes** importance in **protecting** the **urban area** by reducing the natural expansion of the flow in riverbanks and land.

Apulia and Venice

Manfredonia

Venice





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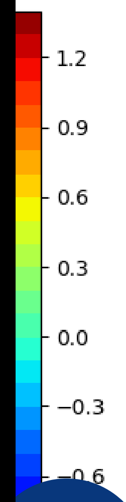
LISFL[redacted]



Venice city

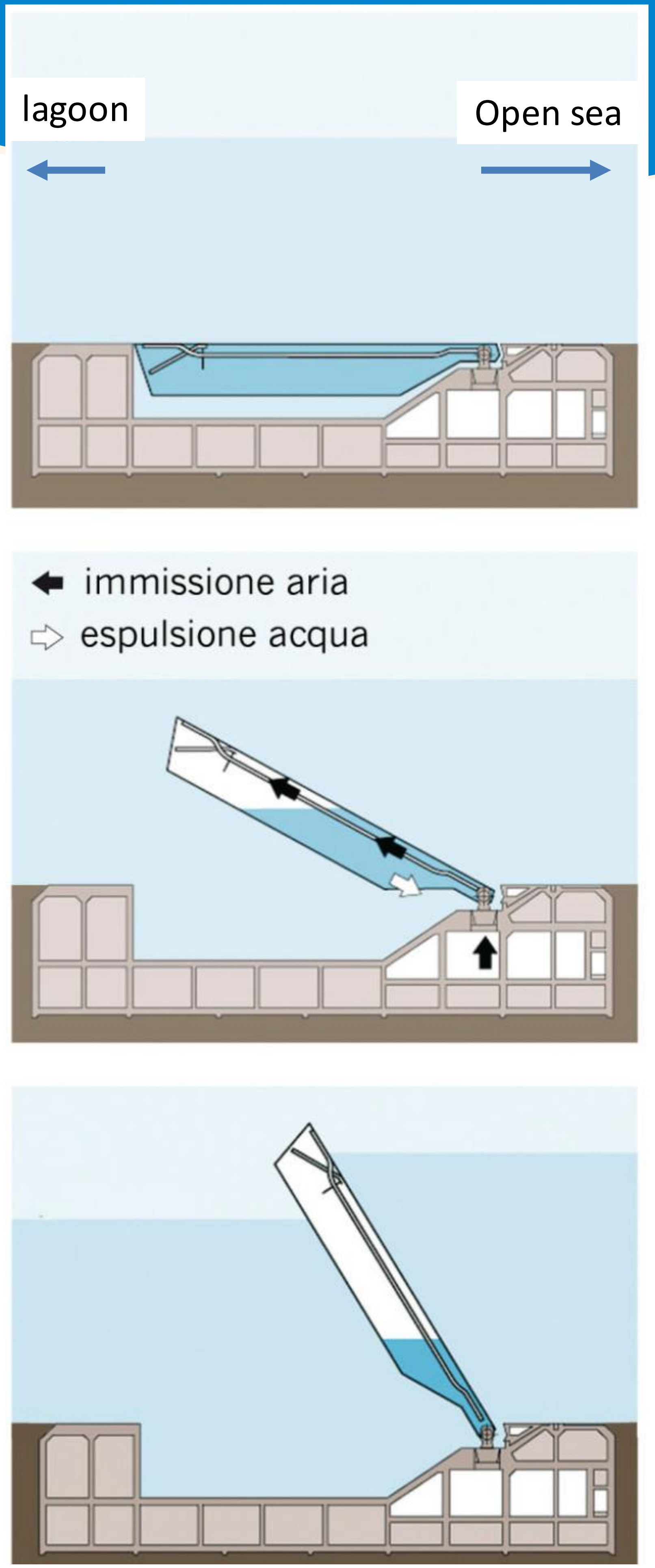
Venice Lagoon

Location of Venice

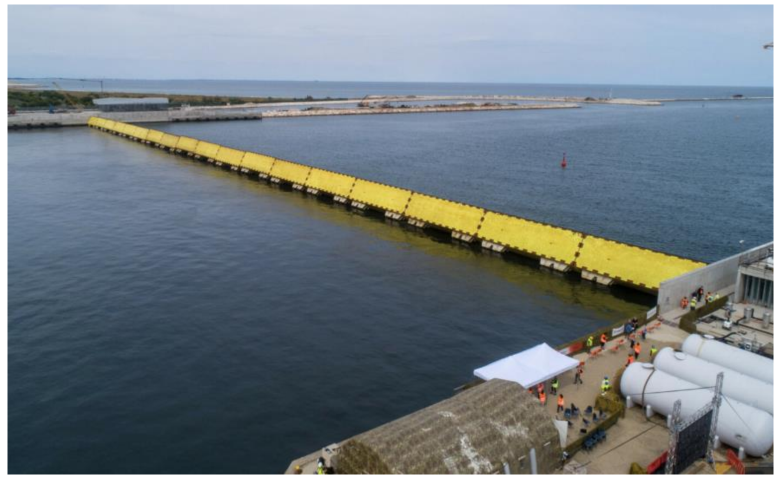
San Marco's square during storm surge

San Marco's square

The Mo.SE Barrier system for protection of the Venice city



Mo.SE open barrier



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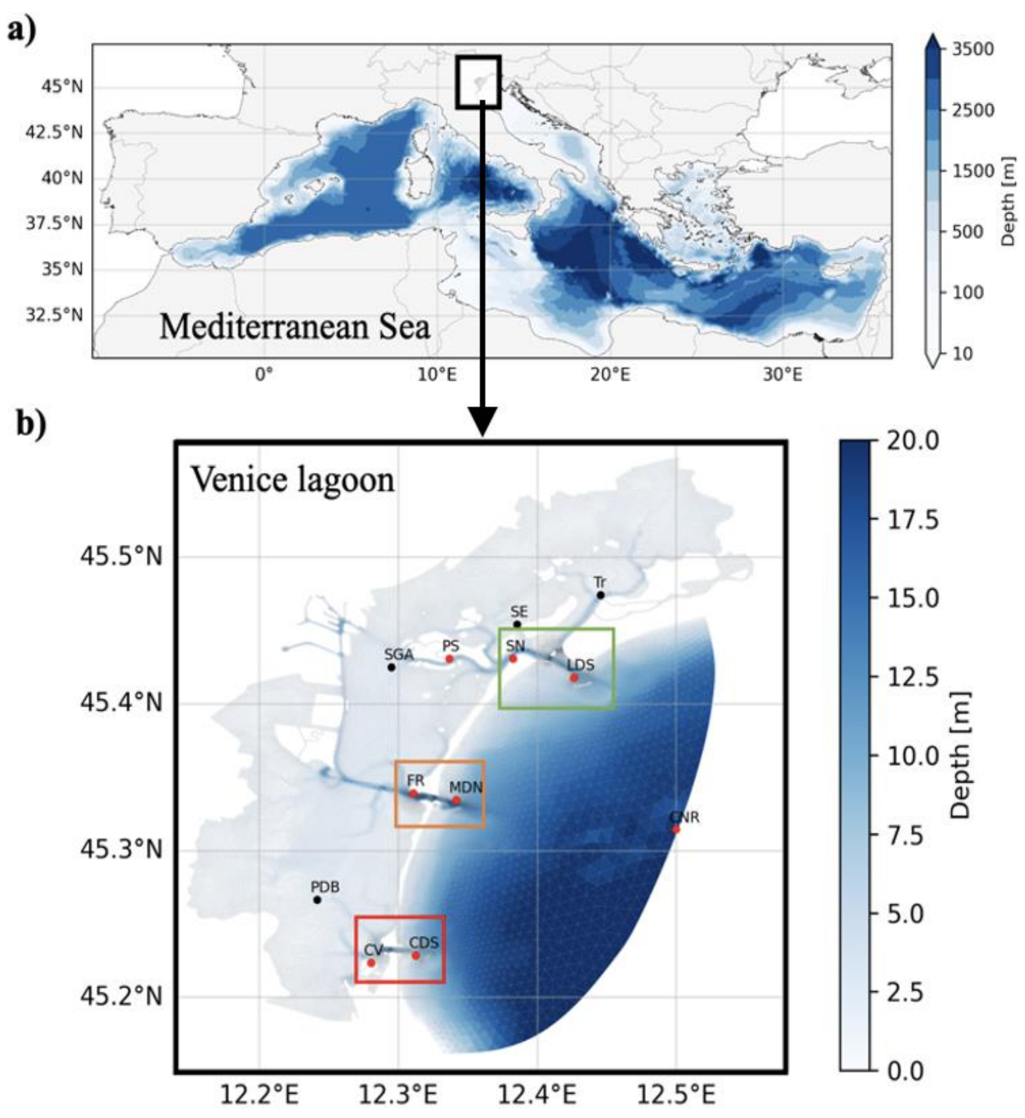
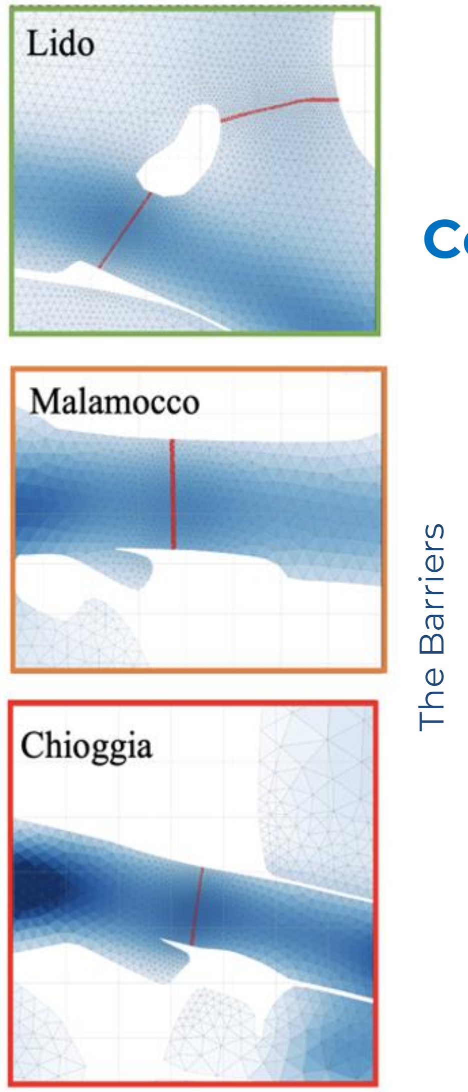
The Venice Lagoon and the MoSE

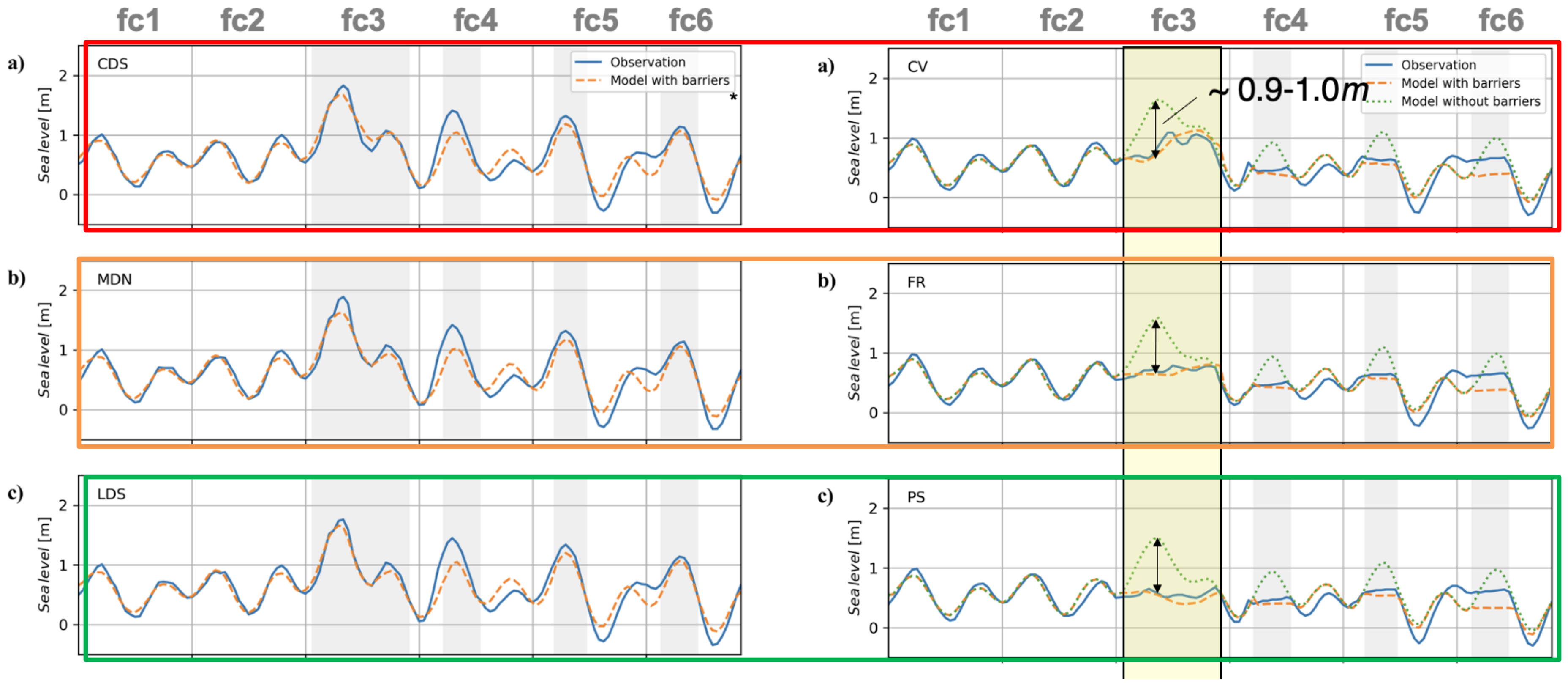




Immersed boundary condition developed in SHYFEM-MPI for simulating the MoSE

Comparison with Tide gauge during The "Acqua Alta" event of Nov. 2022

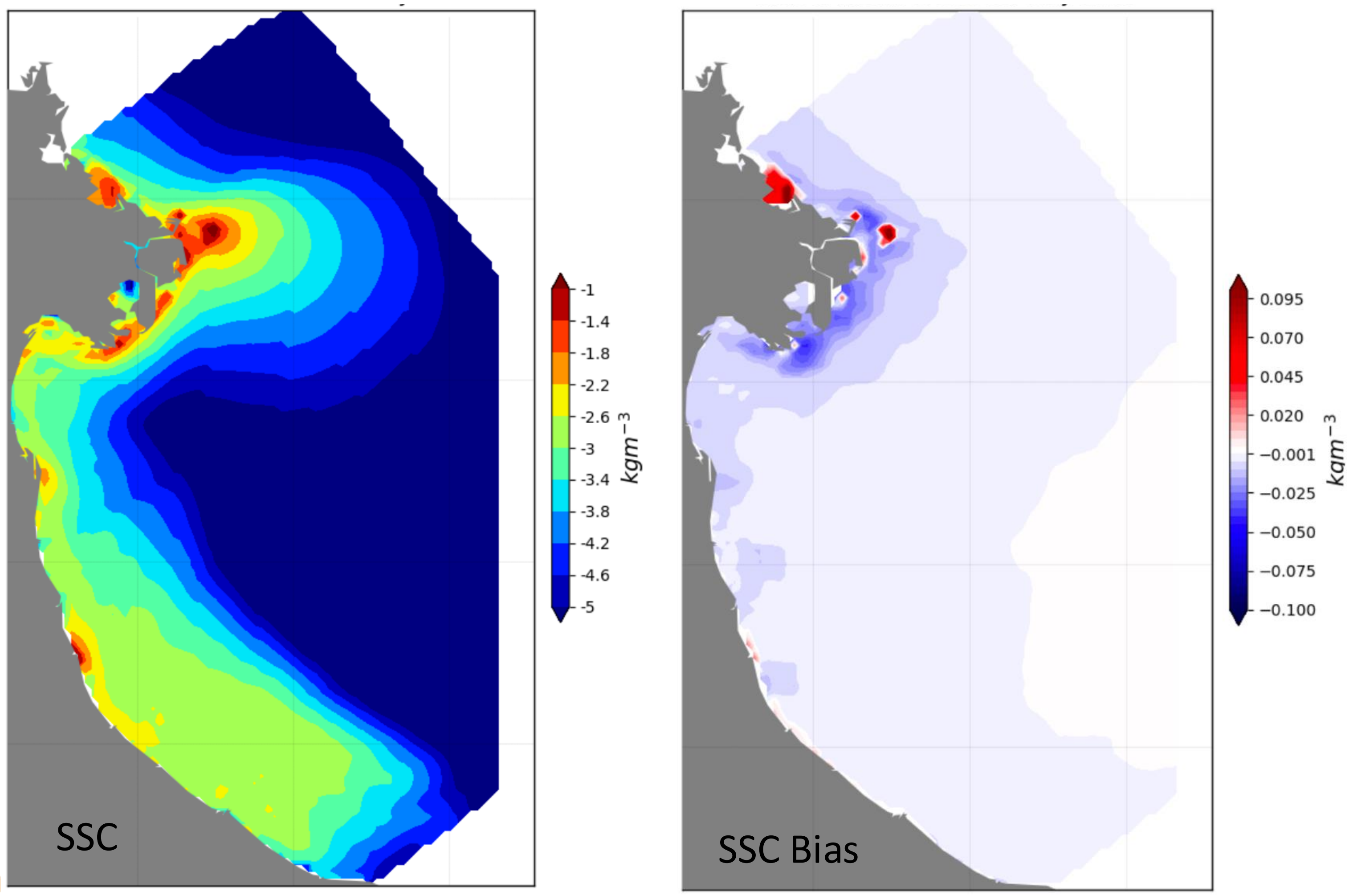
Outside the lagoon — *Inside* the lagoon



Coastal erosion

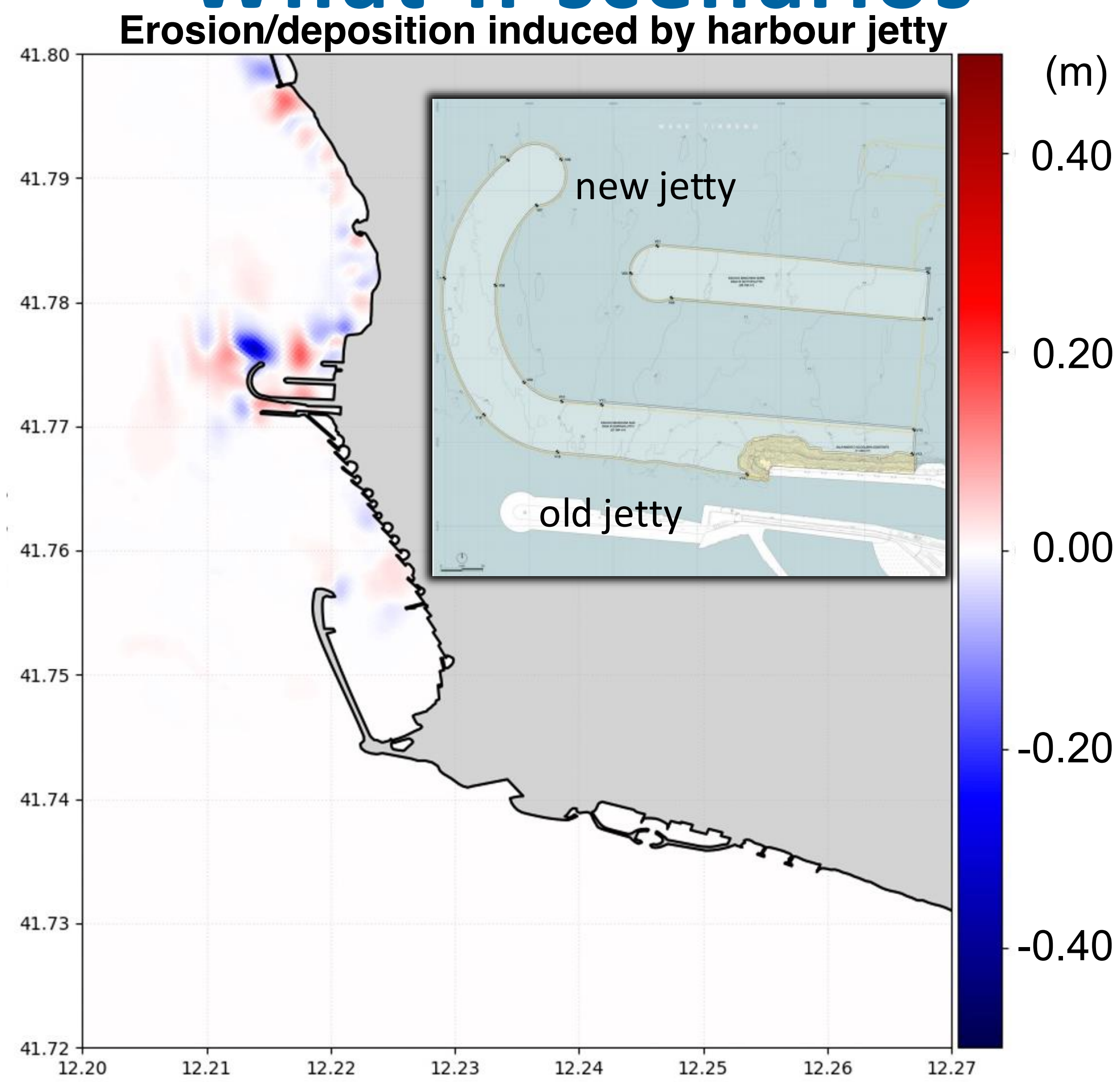
Integration of **sediment transport** module in the coupled modelling framework

Model – Satellite



Sediment Suspended Concentration for Emilia Romagna [Kg/m3]

What-if scenarios



Evaluation of **sediment dynamics** impacted by the construction of a harbor jetty in Fiumicino.

How would you define this?

Banquettes of *P.oceanica*
from Gómez-Pujol et al.,2013

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From issue … to resource

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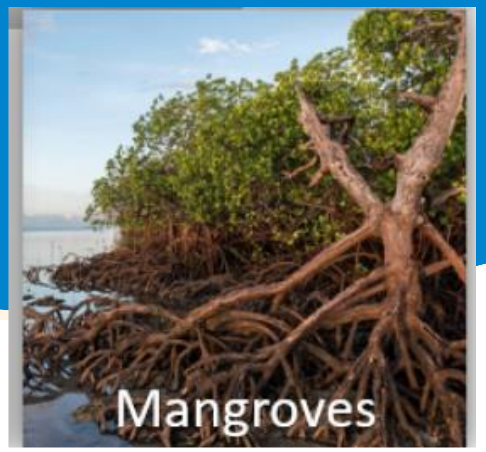
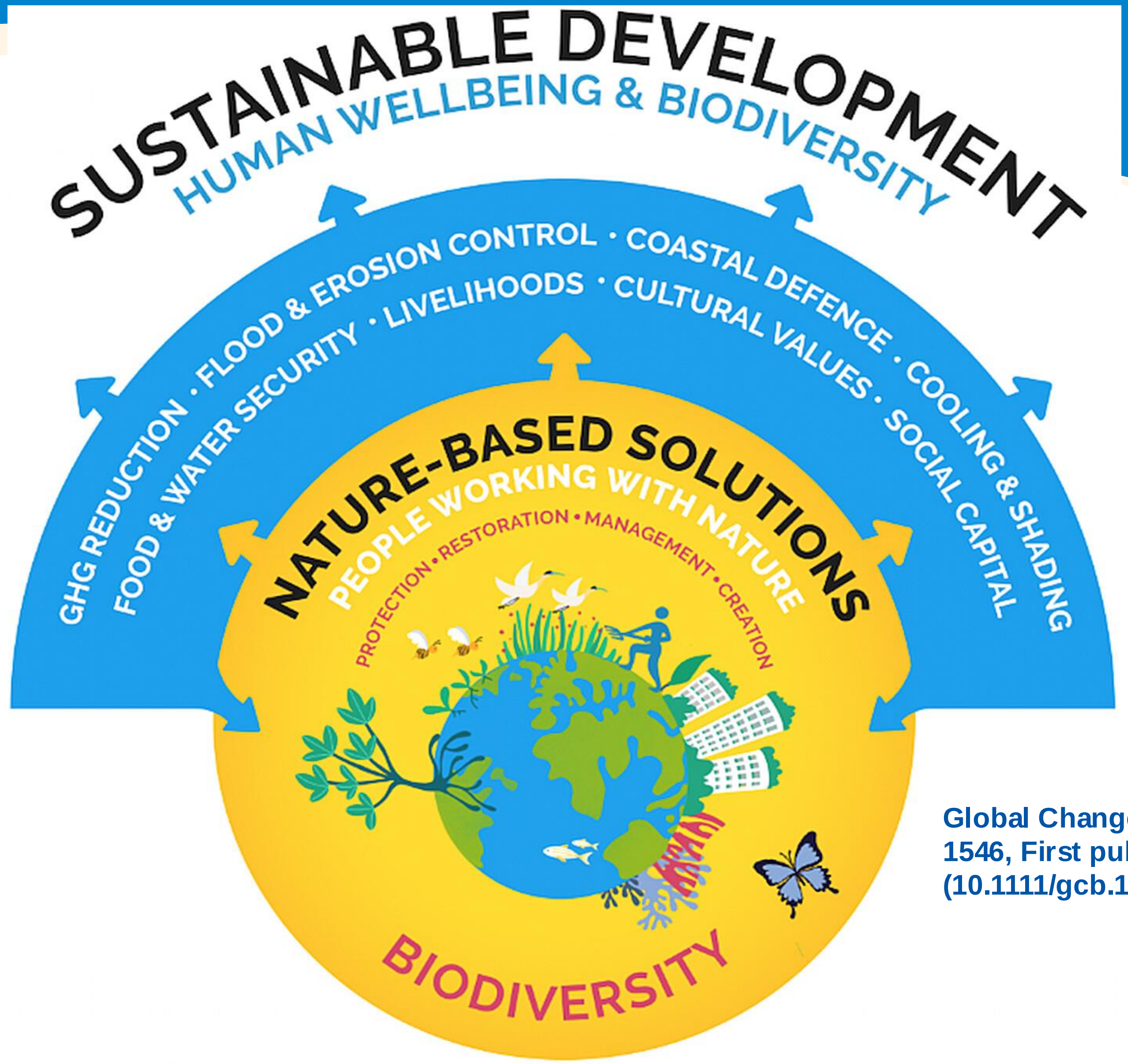
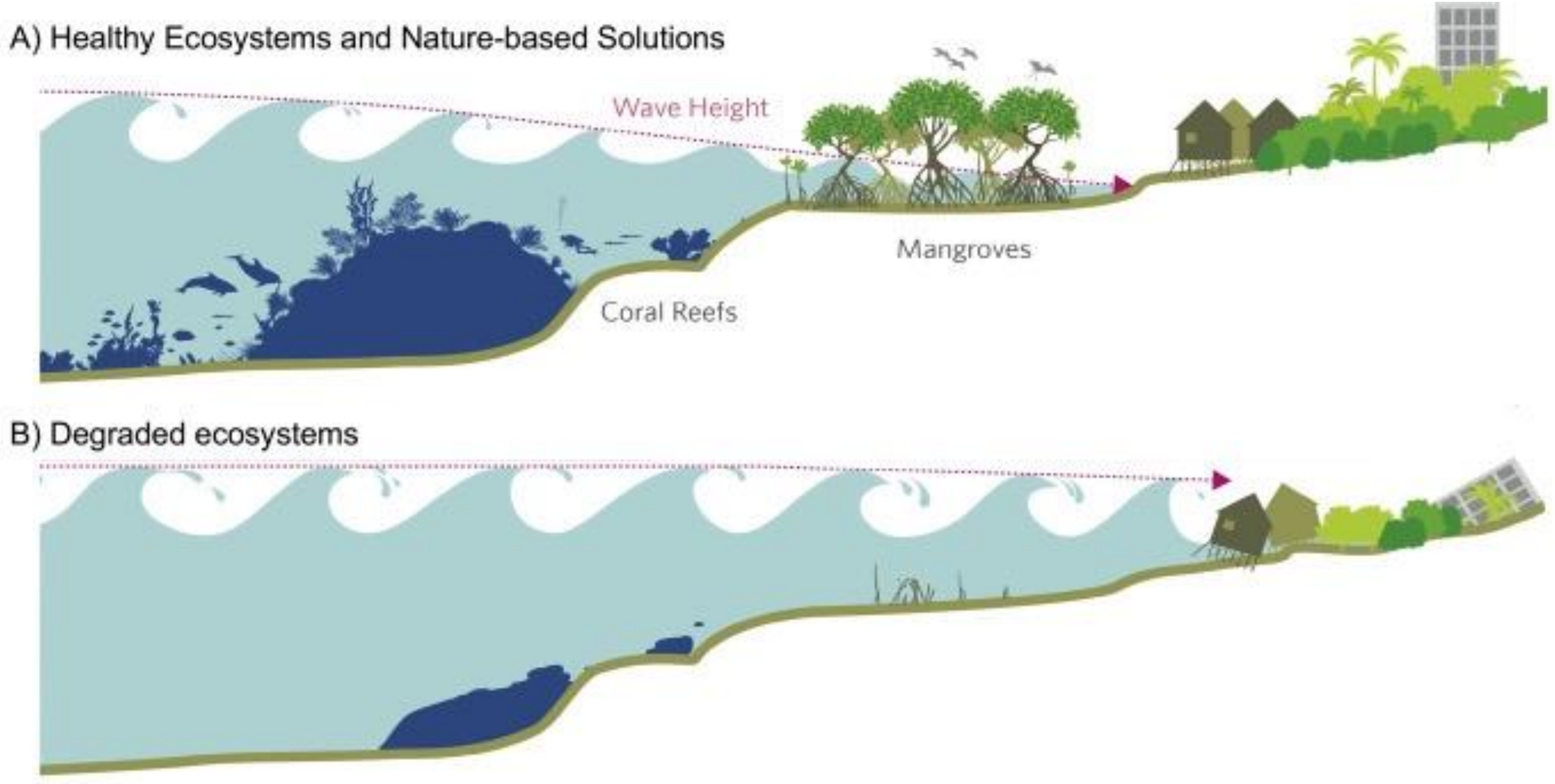
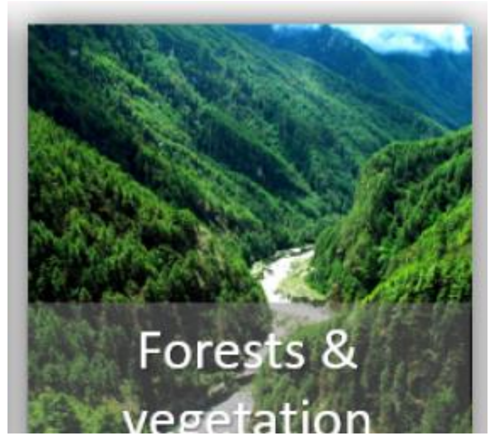




Global Change Biology, Volume: 27, Issue: 8, Pages: 1518-1546, First published: 01 February 2021, DOI: (10.1111/gcb.15513)





Ruckelshaus et al., 2020

Ecosystem services: importance of seagrasses

SHELTER
HABITAT CORRIDOR
BIODIVERSITY
NURSERY AREA
FOOD

FIBERS
BIOMASS

OXYGEN
CARBON STORAGE
NUTRIENT CYCLING
WATER QUALITY

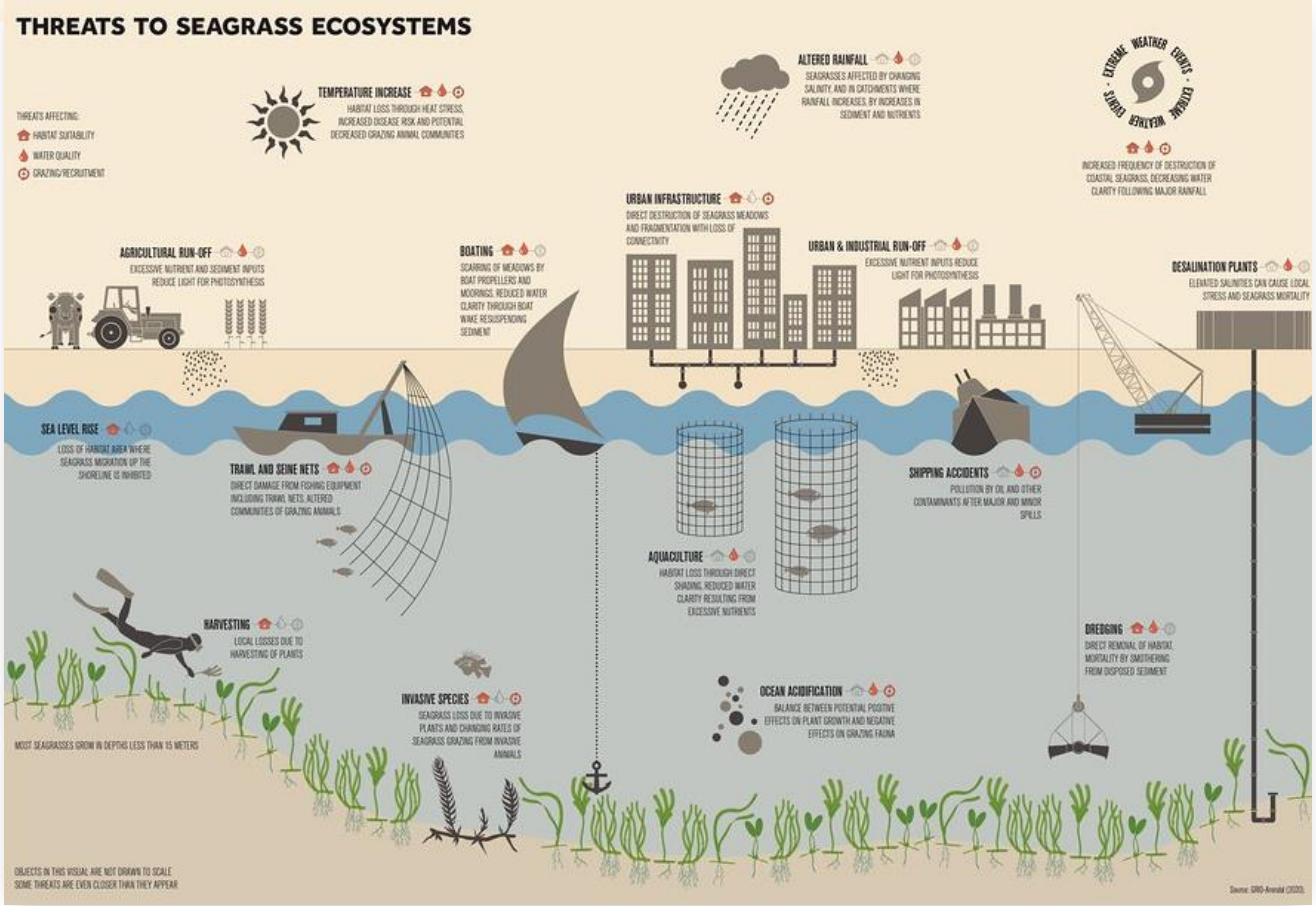
CLIMATE RESILIENCE
LIVELIHOODS

COASTAL PROTECTION
WAVE DAMPING
CURRENTS DAMPING
SEDIMENT TRAPPING
SEDIMENT STABILIZATION

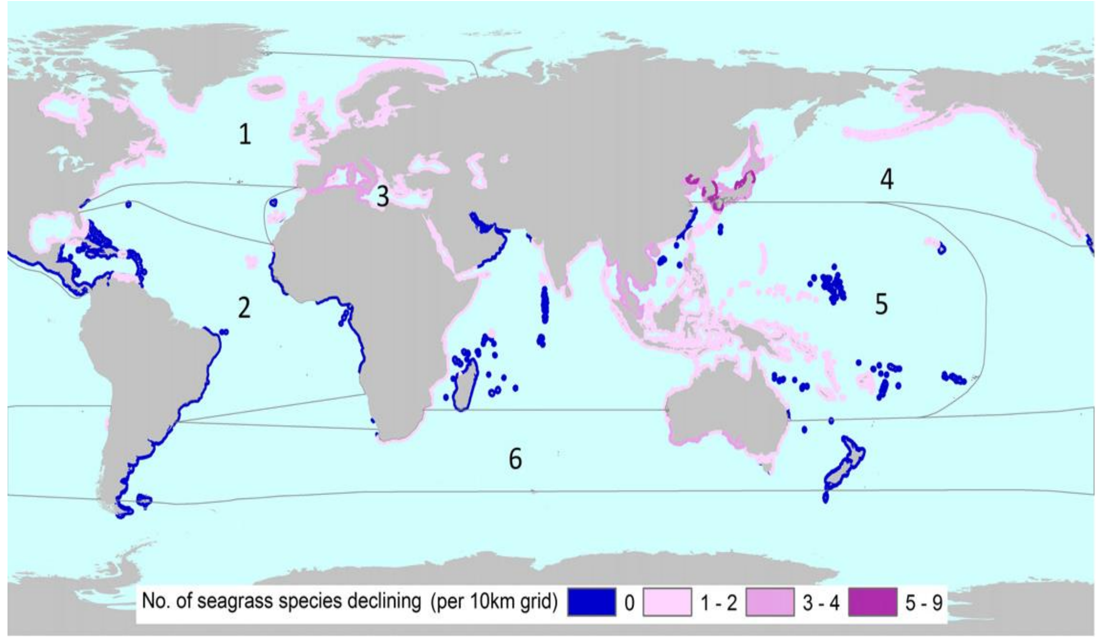
They are able to grow, self-repair, and adapt

COASTAL RESILIENCE SCHOOL

Threats to seagrass



- **Threats can be land-based, sea-based, climate related**
- **Global decline since 1930**



(Short et al., 2011)

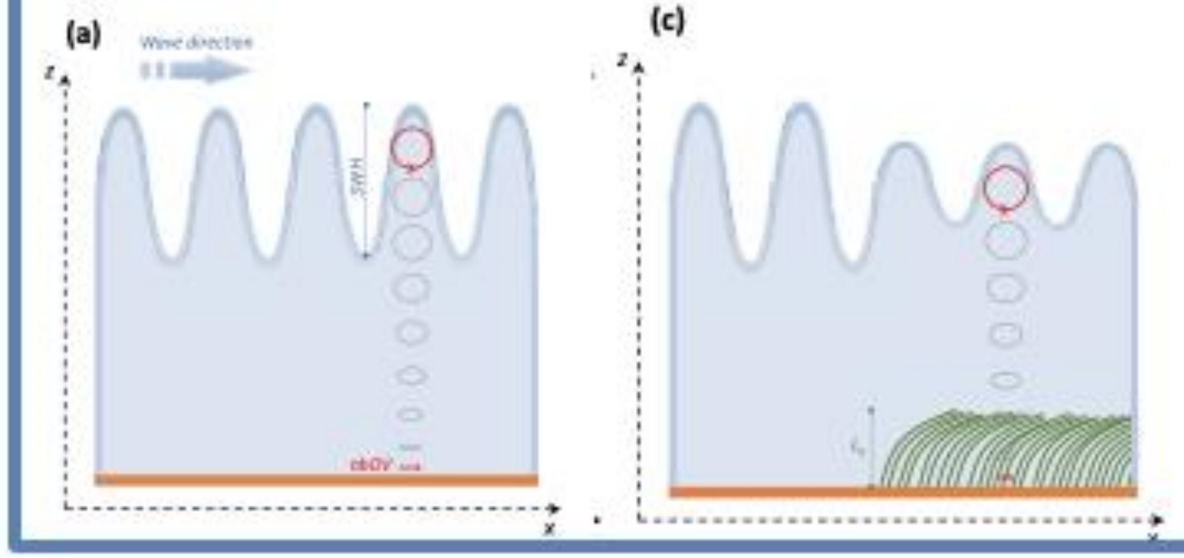
Seagrass in numerical models

$$\frac{DN}{Dt} = \sum S\ ; \qquad S_{tot} = Sin + S_{ds} + S_{nl} + S_{tr} + S_{bot} + S_{db}$$

Wave dissipation induced by vegetation

$$S_{bot} = S_{bot} + S_{ds,veg}$$

$$S_{d,\ veg} = -\sqrt{\frac{2}{\pi}}\, g^2 \widetilde{C_D} b_v n_v \left(\frac{\tilde{k}}{\tilde{\sigma}}\right)^3 \frac{sinh^3(\tilde{k} l_e) + 3 sinh(\tilde{k} l_e)}{3\tilde{k} cosh^3(\tilde{k} h)} \sqrt{E_{tot}}\, E(\sigma, \theta)$$



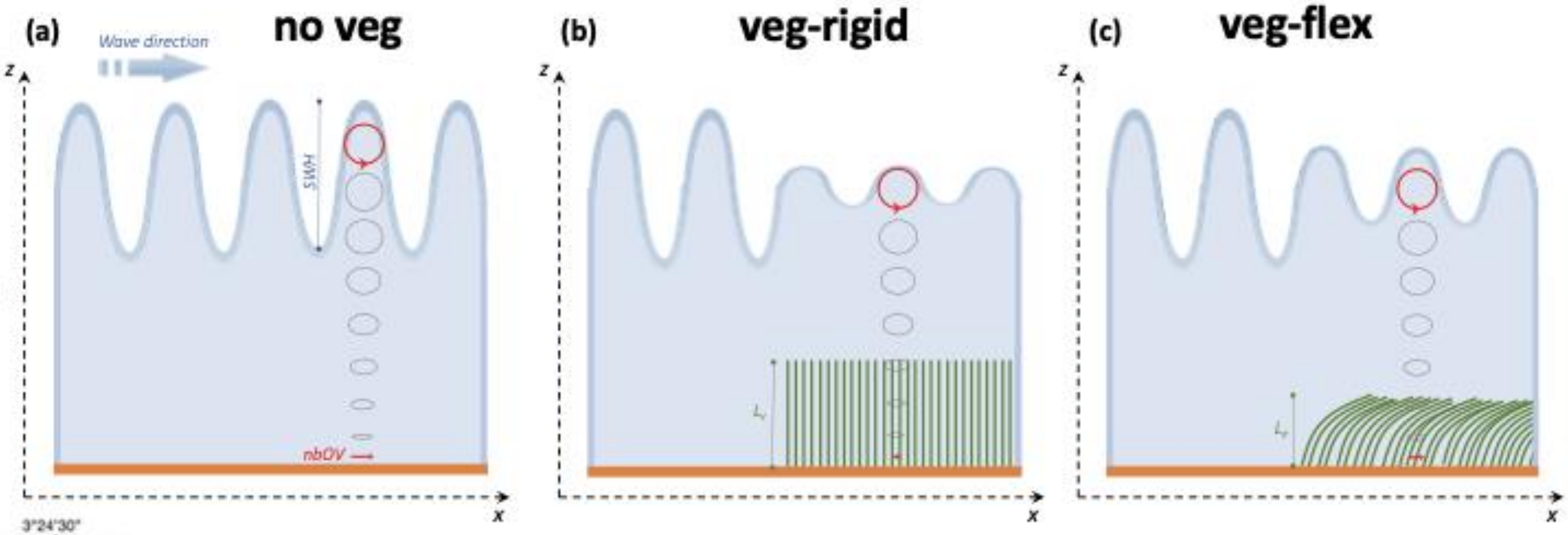
N_v = no. of plants/m^2 *(literature)*
b_v = vegetation width *(literature)*
C_D = drag coefficient *(literature)*
l_e = effective vegetation length

Phenotypic traits as model input

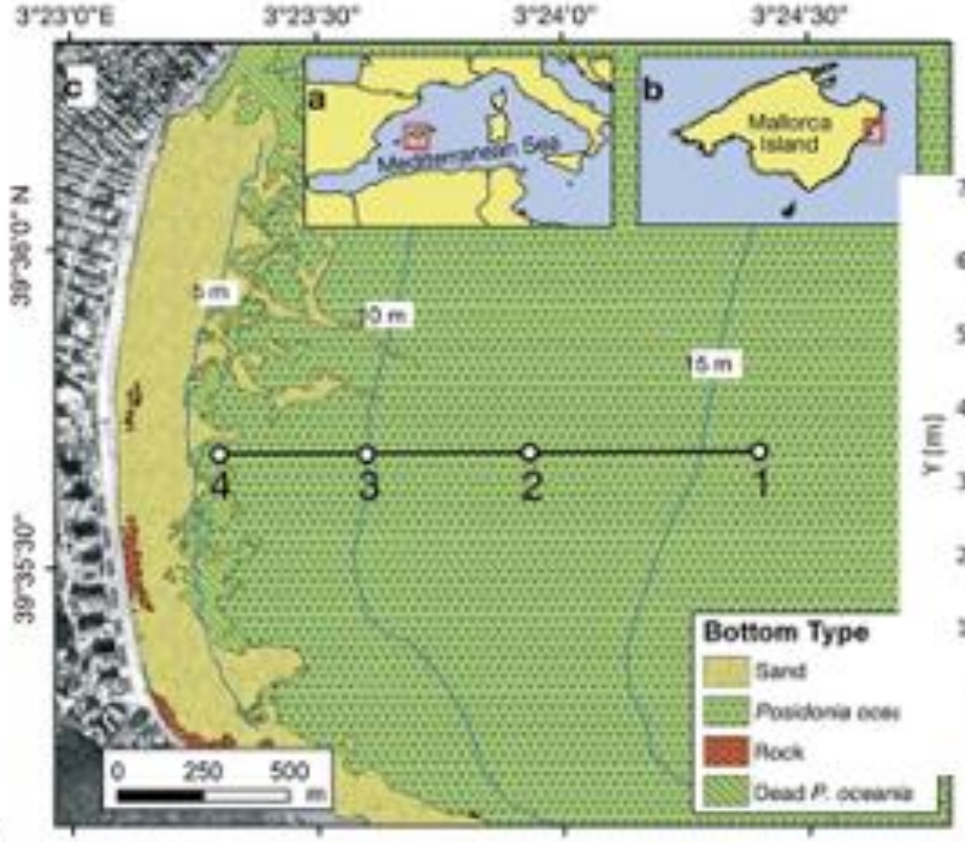
- ✓ No. of plants per area
- ✓ Leaf length
- ✓ Leaf width
- ✓ Leaf thickness
- ✓ Tissue density

Idealized experiment from Infantes et al., 2012

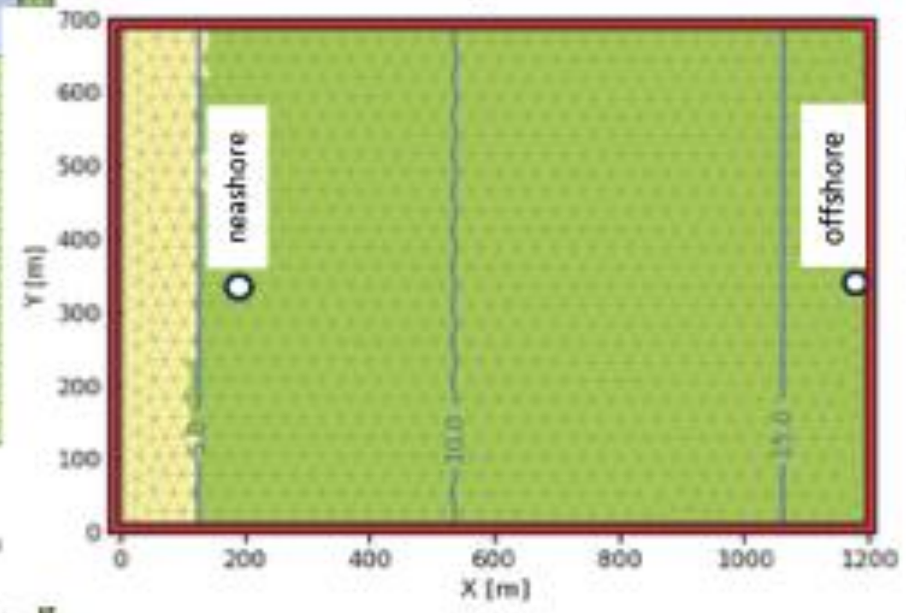
Measurement of SWH on seagrass meadows

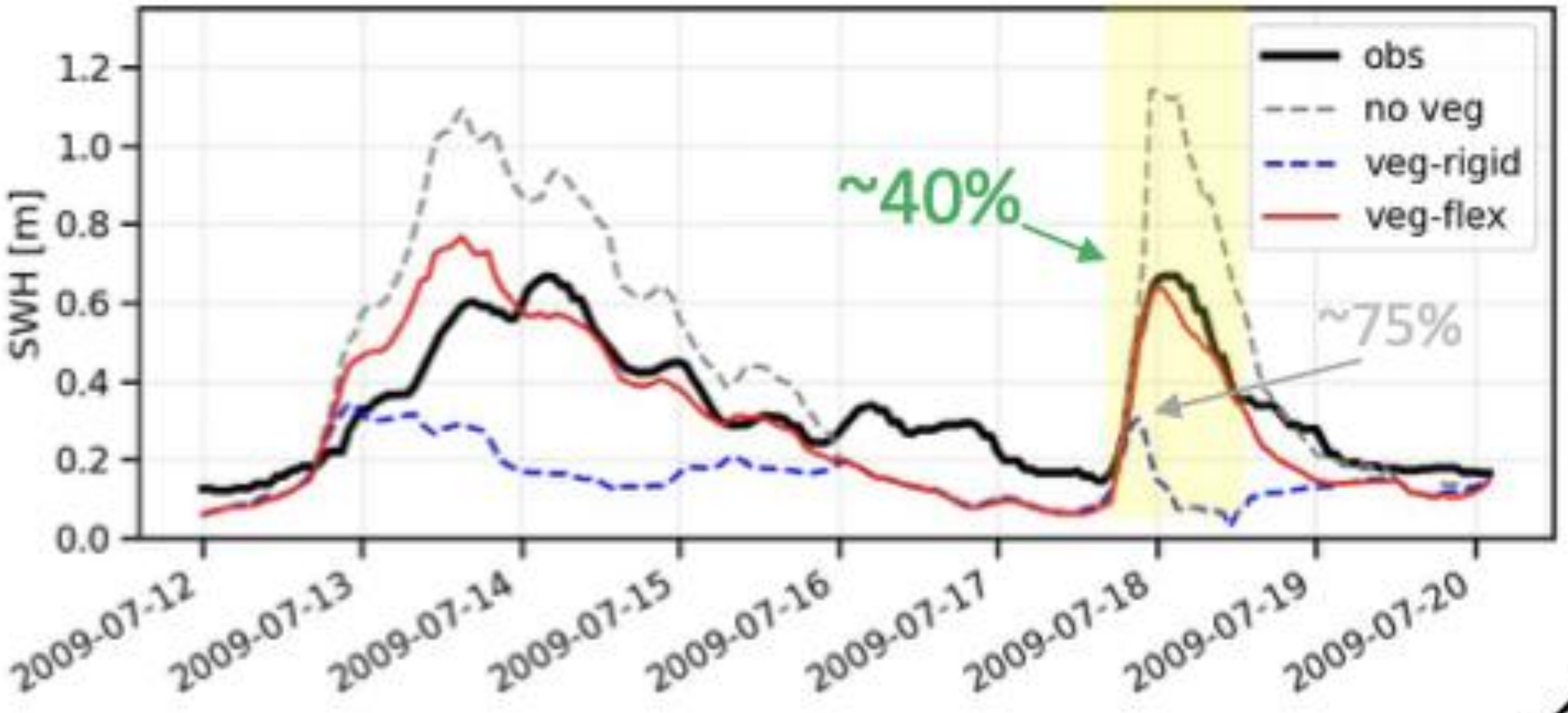


Cala Millor, Mallorca, Spain

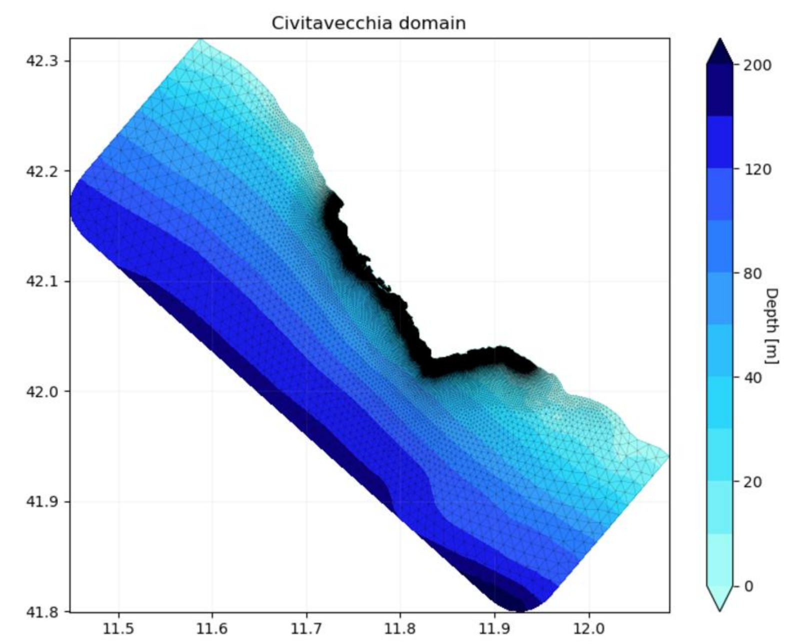


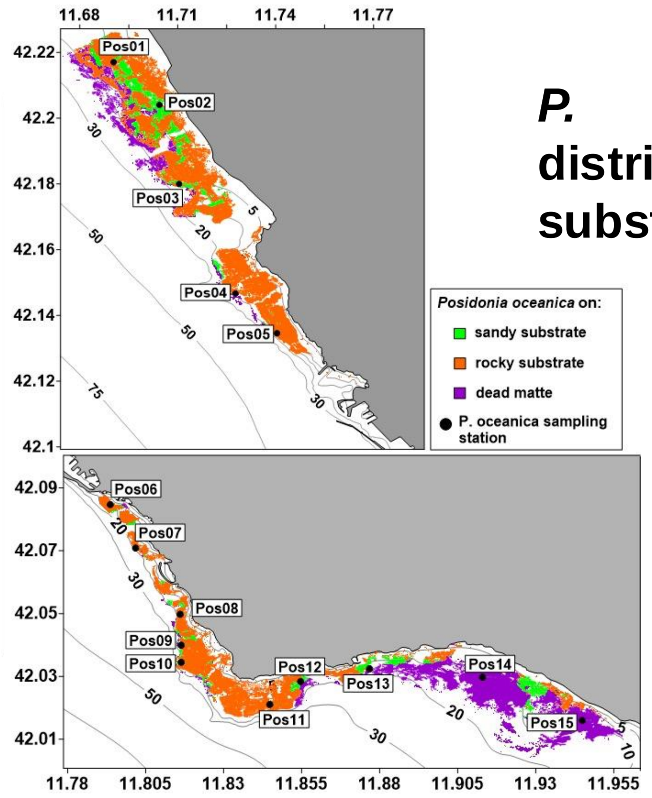
Numerical representation





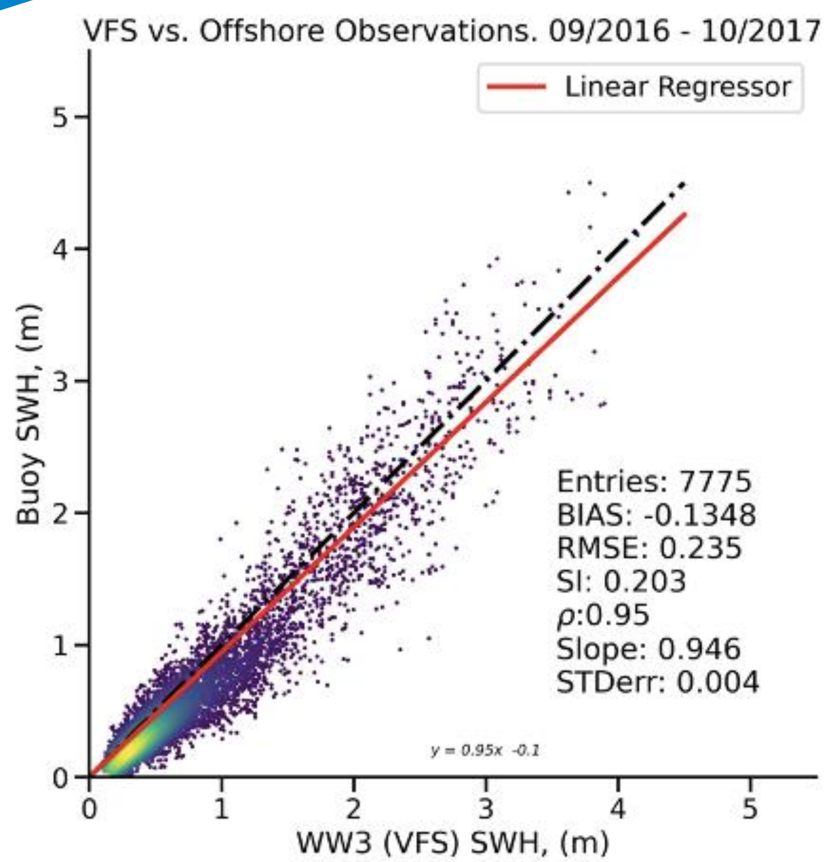
Lazio coast and Civitavecchia harbour in Tyrrhenian Sea





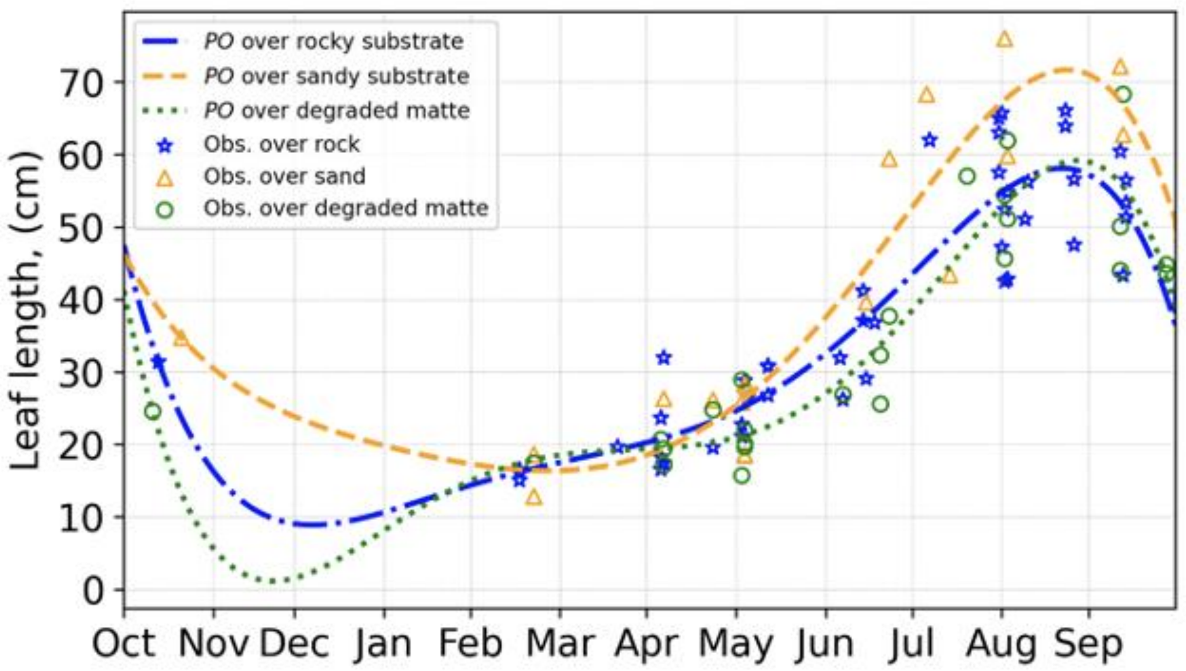
***P. oceanica* distribution and substrates**

Enhancing realism in modelling nature

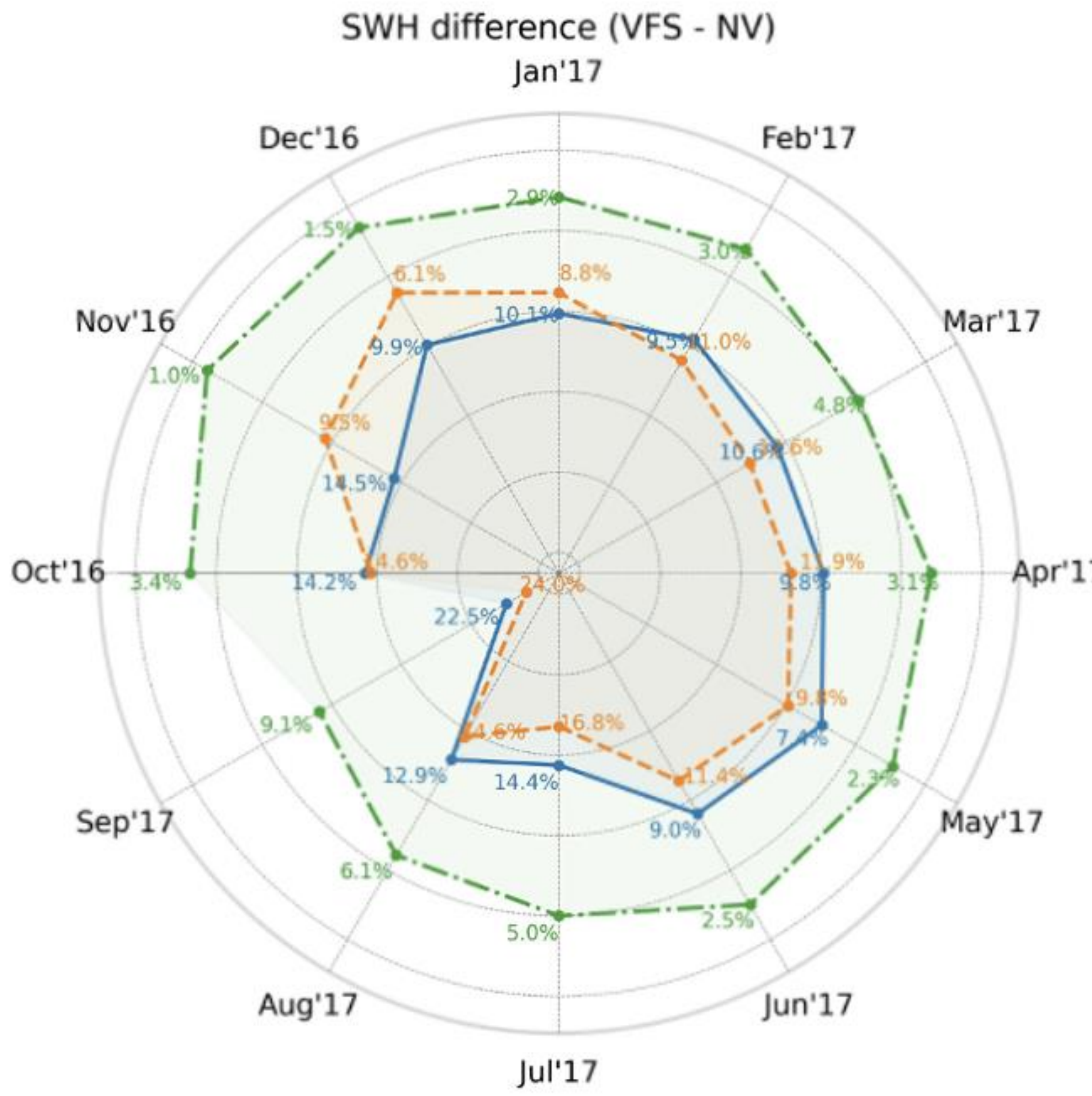


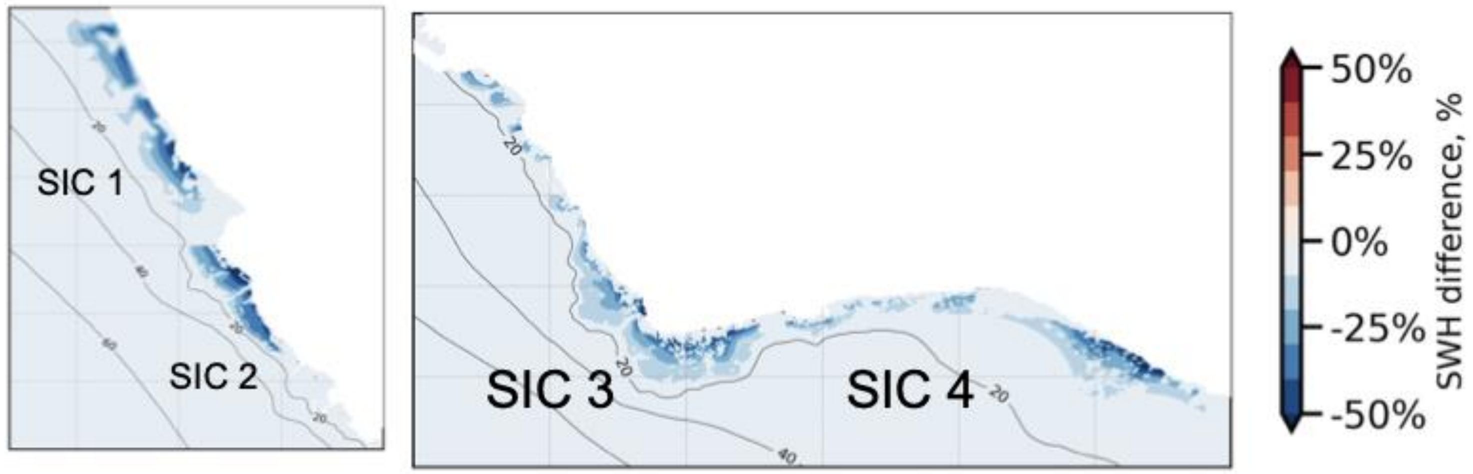
Wave model validation vs buoy

Leaf length seasonality derived from in-situ surveys

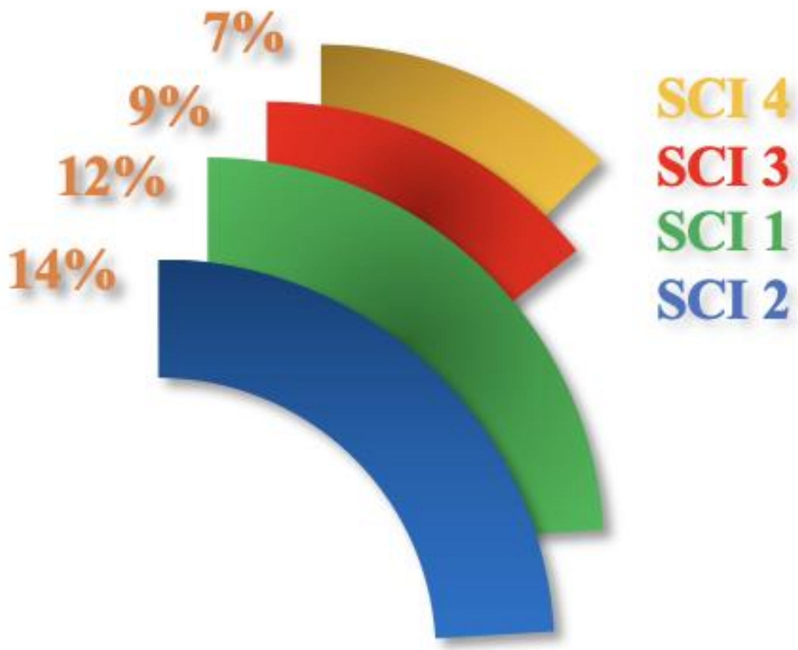


Monthly wave attenuation for different ecotype





Characterization of the Annual mean dissipation of SWH in the different SCIs



Wave attenuation per SCI

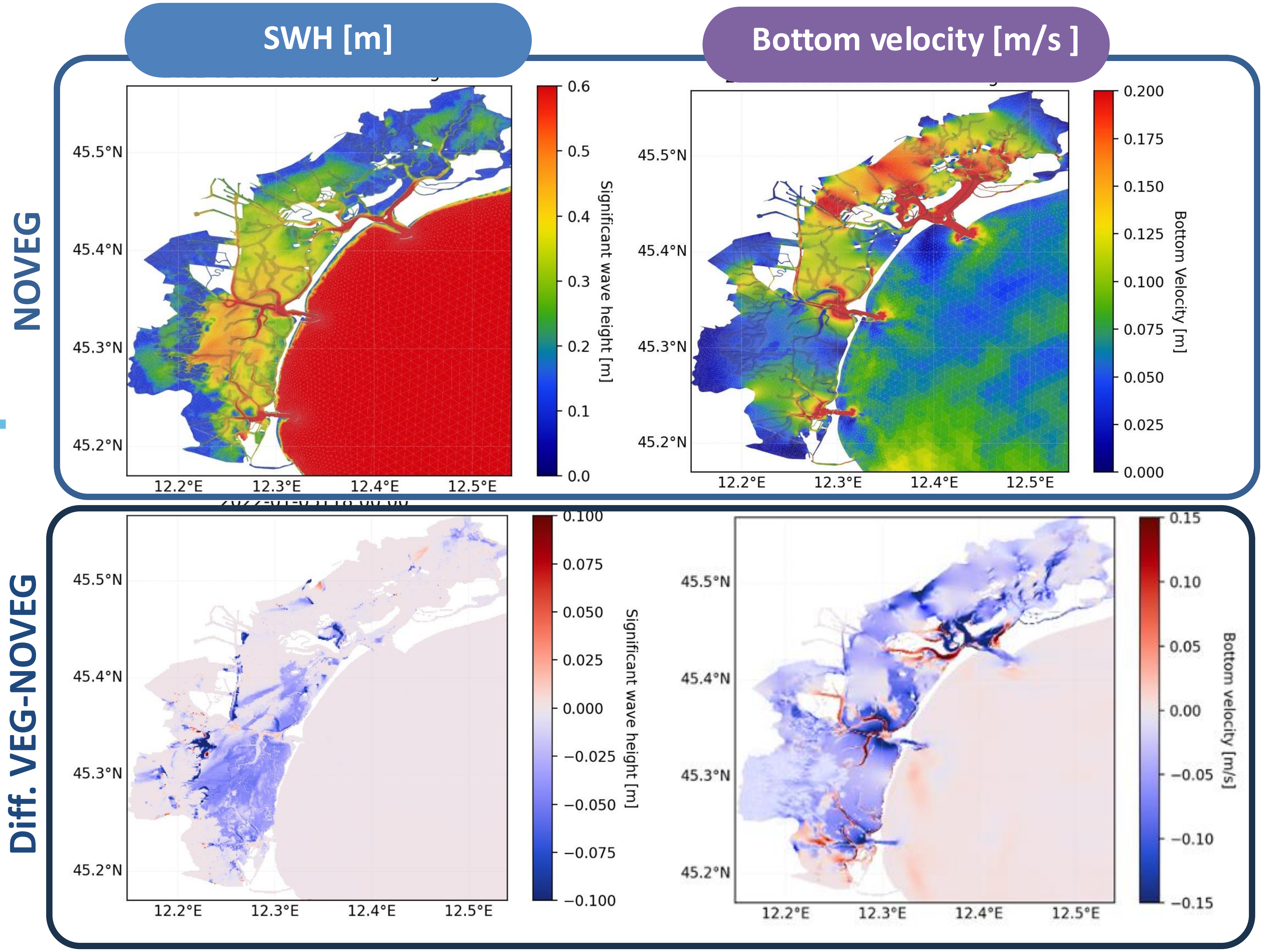
Applications of the DTO

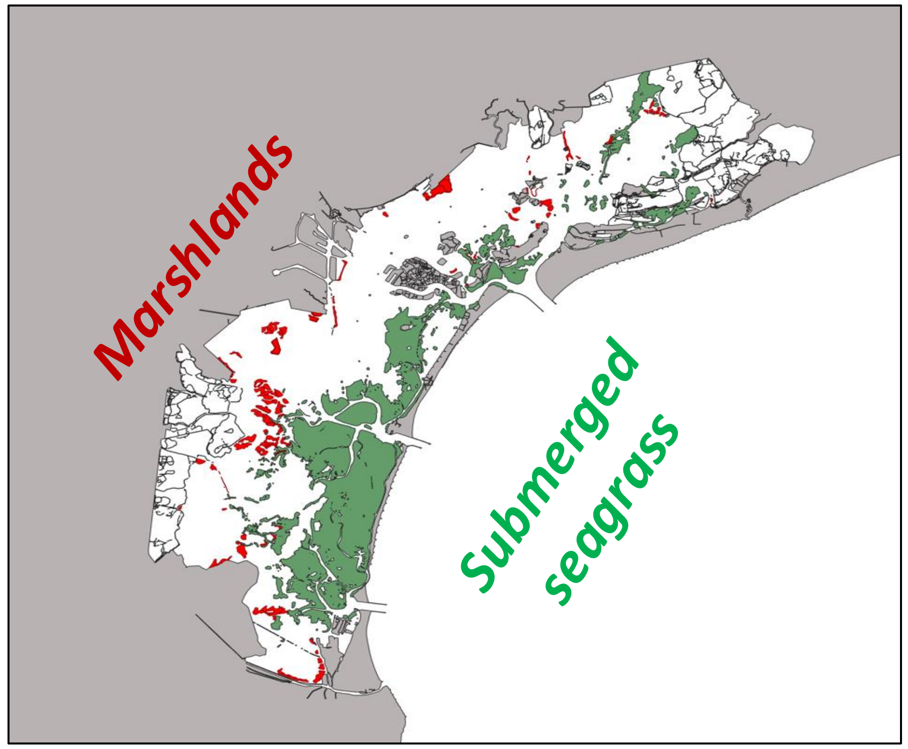
In RESTCOAST project, **RAAS** and **GOCO** divisions investigated the impact of vegetation and marshlands at Venice lagoon on waves, sea level and water currents at bottom

Venice lagoon

Assessment of the coastal protection provided by the seagrass

REST~COAST





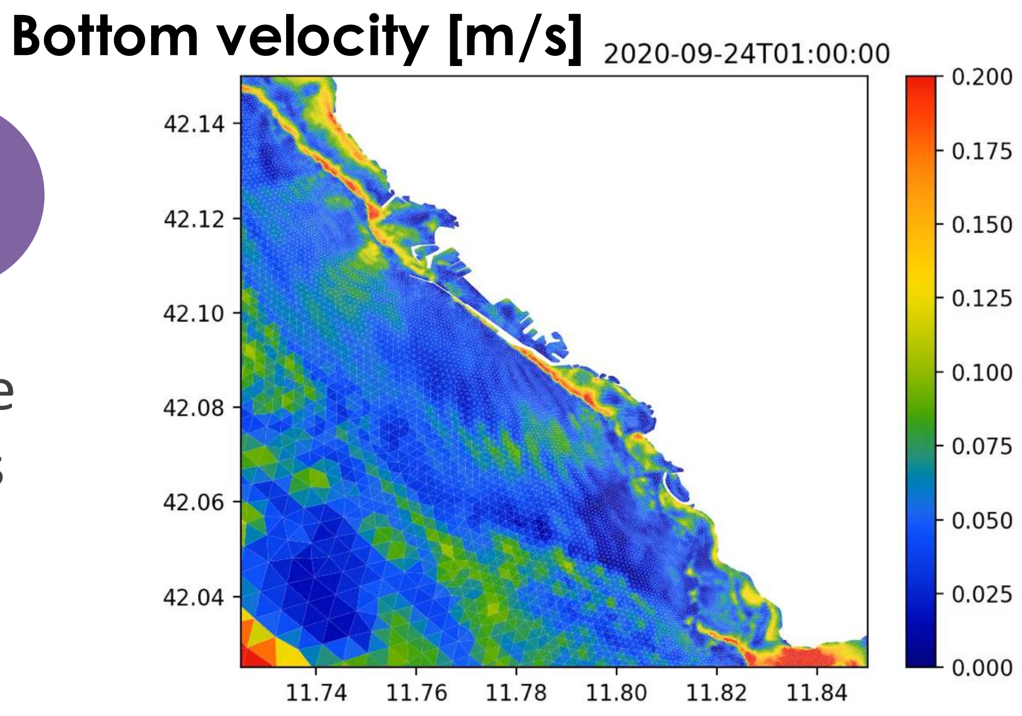
- **Decrease of wave height** (~10%) resembling the distribution of seagrass
- **Large decrease for bottom velocity** more generalized.

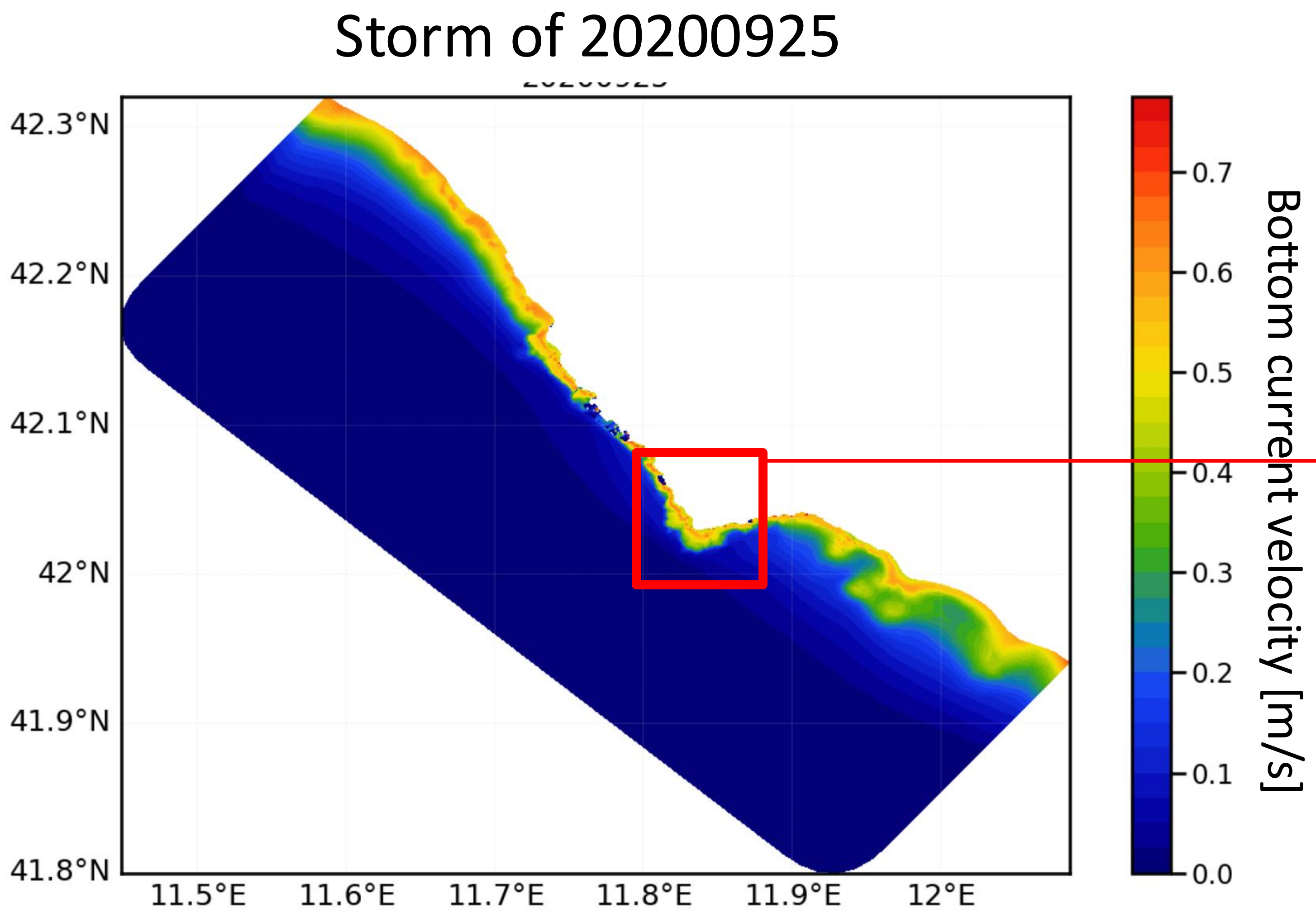
COASTAL RESILIENCE SCHOOL

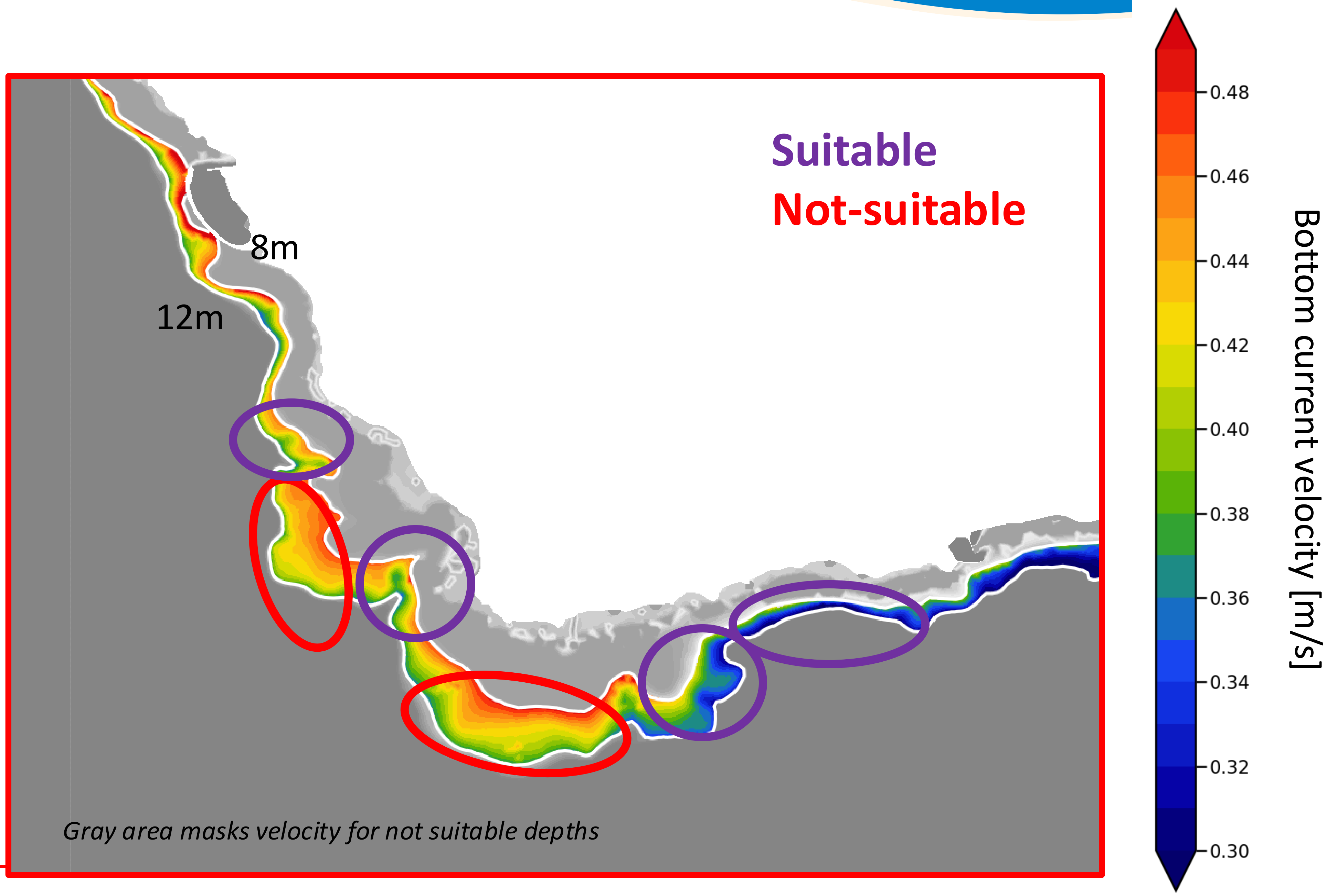
Applications of the DTO

Civitavecchia littoral

Identification ex-ante of the best location for a seagrass restoration activity



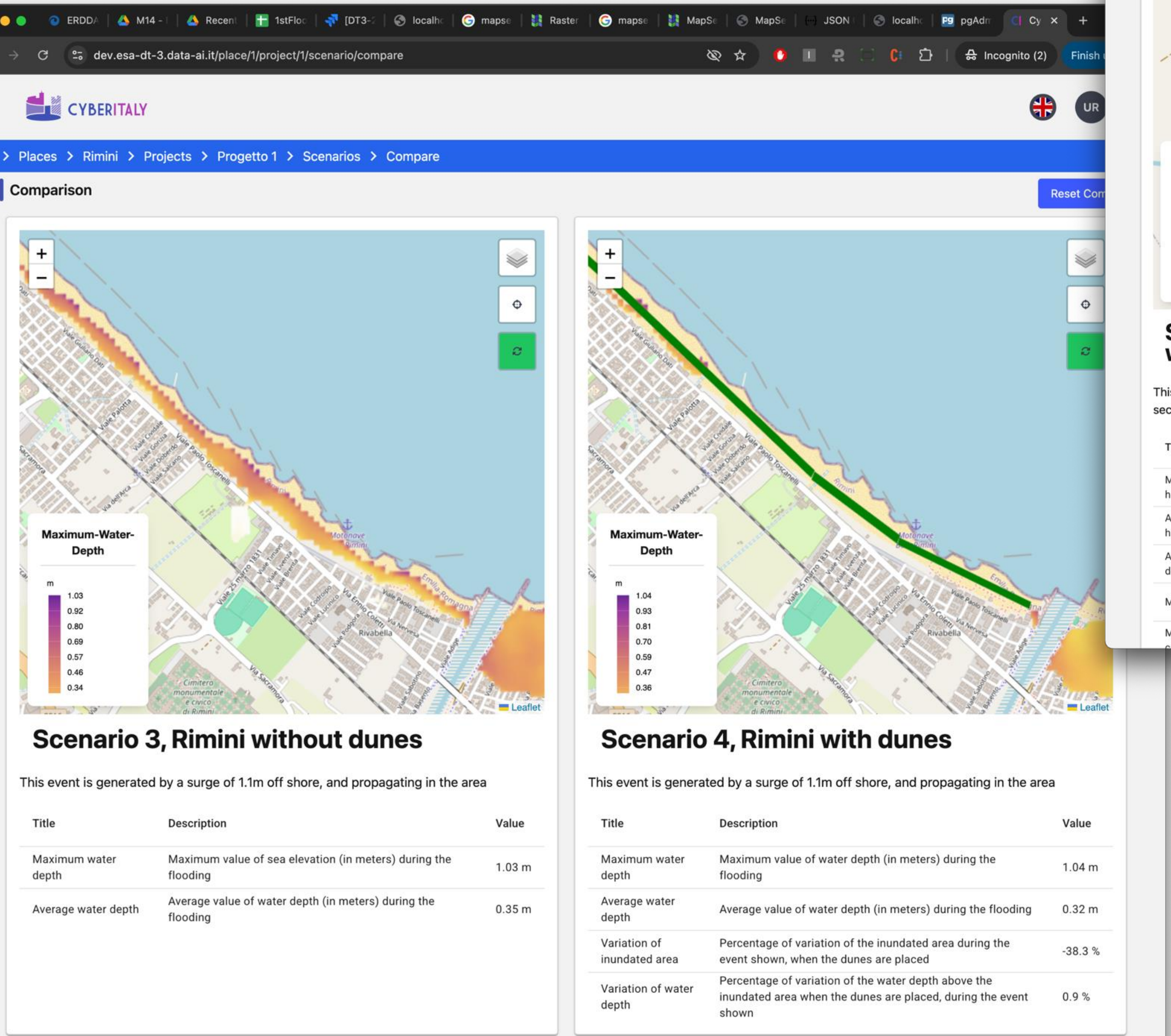


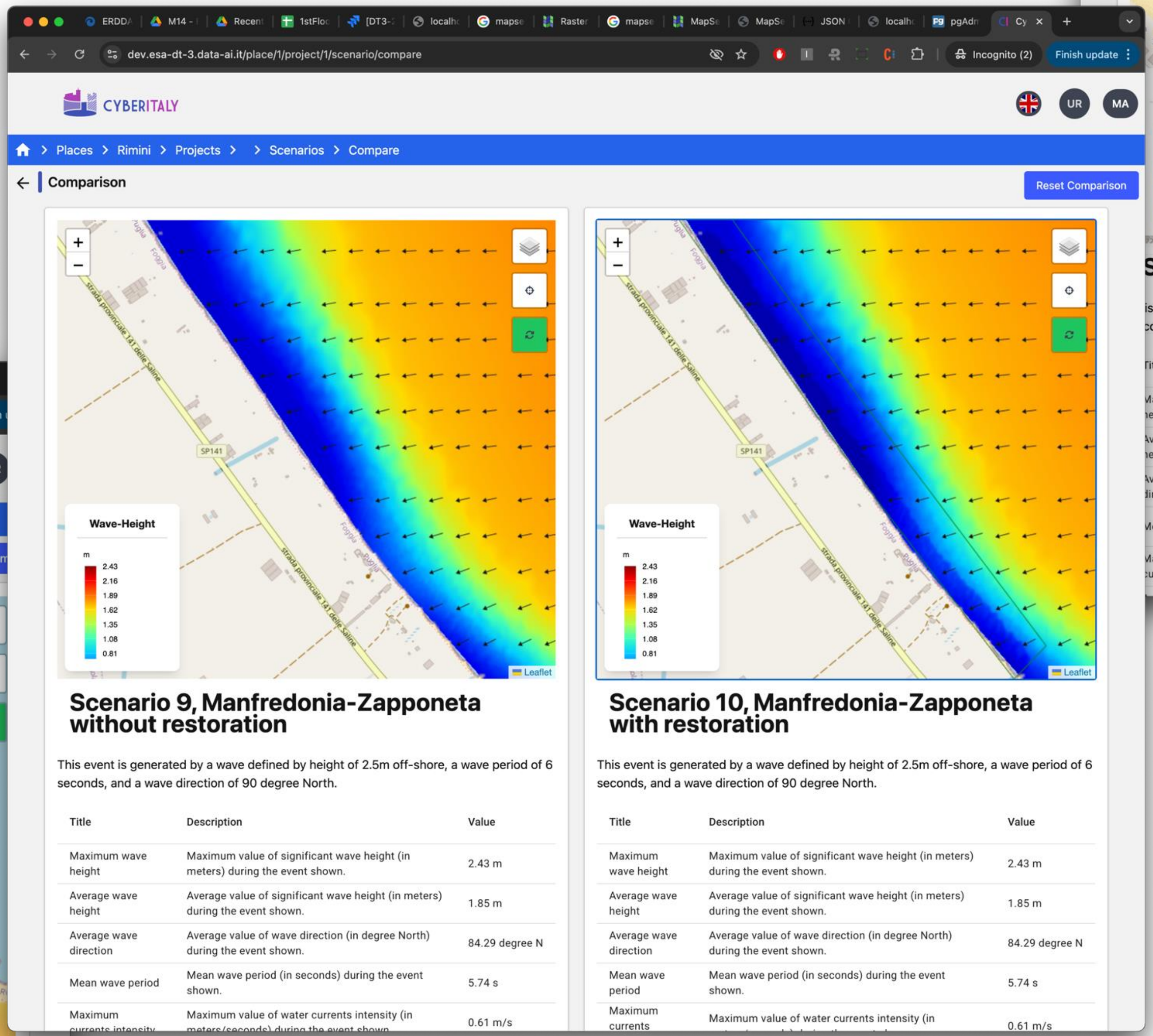


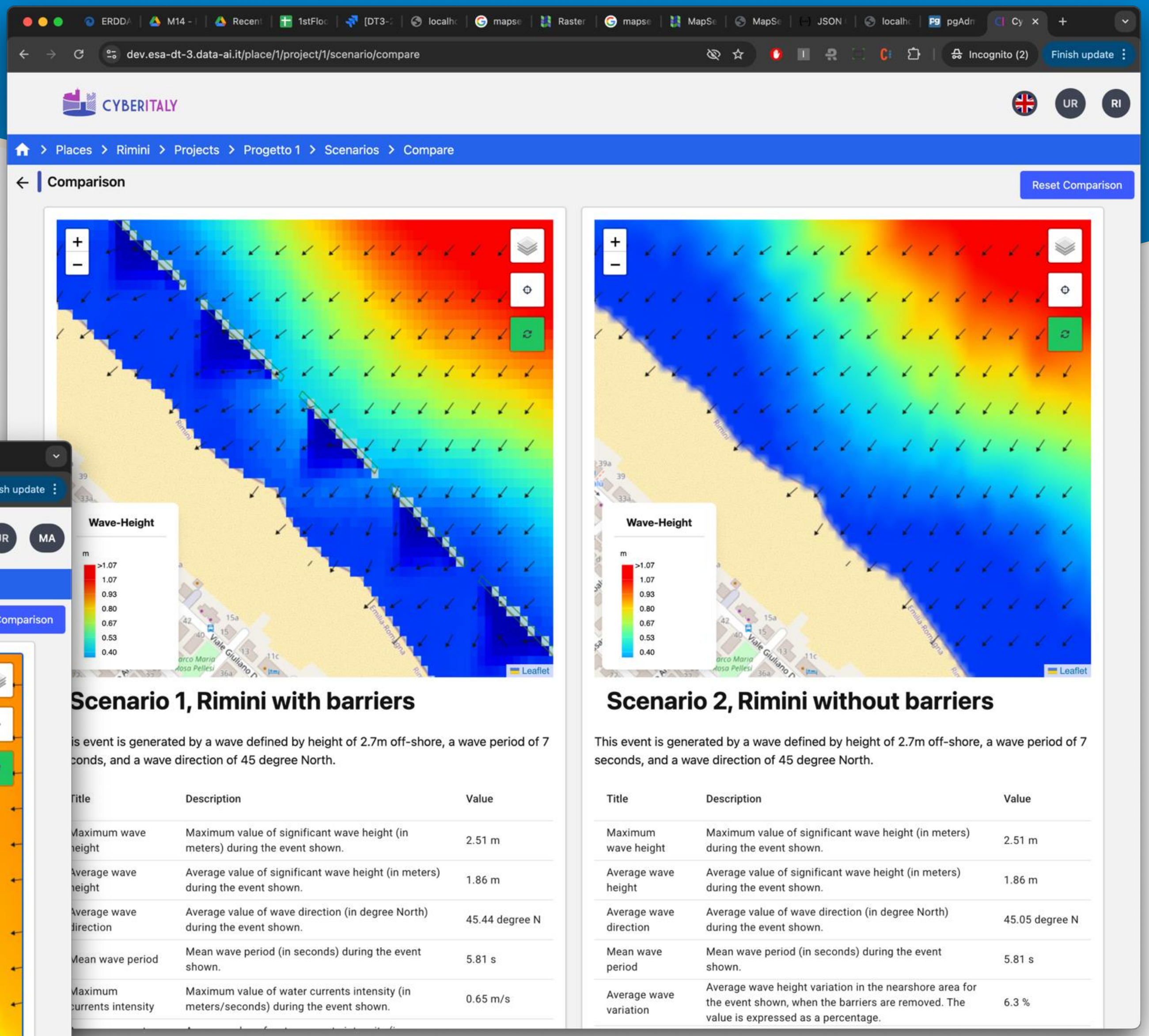
After the identification of the suitable areas (in **purple**), scientific divers will check in-situ what are the best locations for re-implantation.

Cyber Italy: DT#3

“winter-dunes” for coastal protection







What-if scenario, barriers removal

Seagrass restoration AI-based

So… where are we heading?

It help us in simulating and understanding the physical environment using observations, models and AI

Manage of computational resources issues

Manage of pre/post-processing

Simulation of what-if scenarios

Simulation on demand

Ease the results interpretation

Process is ongoing… but still a lot to do

COASTAL RESILIENCE SCHOOL

THANK YOU!

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ADDITIONAL LINKS: www.cmcc.it

unesco Intergovernmental Oceanographic Commission

UN Decade Collaborative Centre for COASTAL RESILIENCE

OTG@ OceanTeacher Global Academy

2021 2030 United Nations Decade of Ocean Science for Sustainable Development