Integrated Coastal Digital Twin Framework:

Enhancing Sustainable, Science-based coastal resilience and adaptation strategies

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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 weather events
Storm surges and coastal flooding
Erosion

Socio-economic

Damage to infrastructure
Economic losses
Population displacement
Loss of human lives

Bio-Ecological

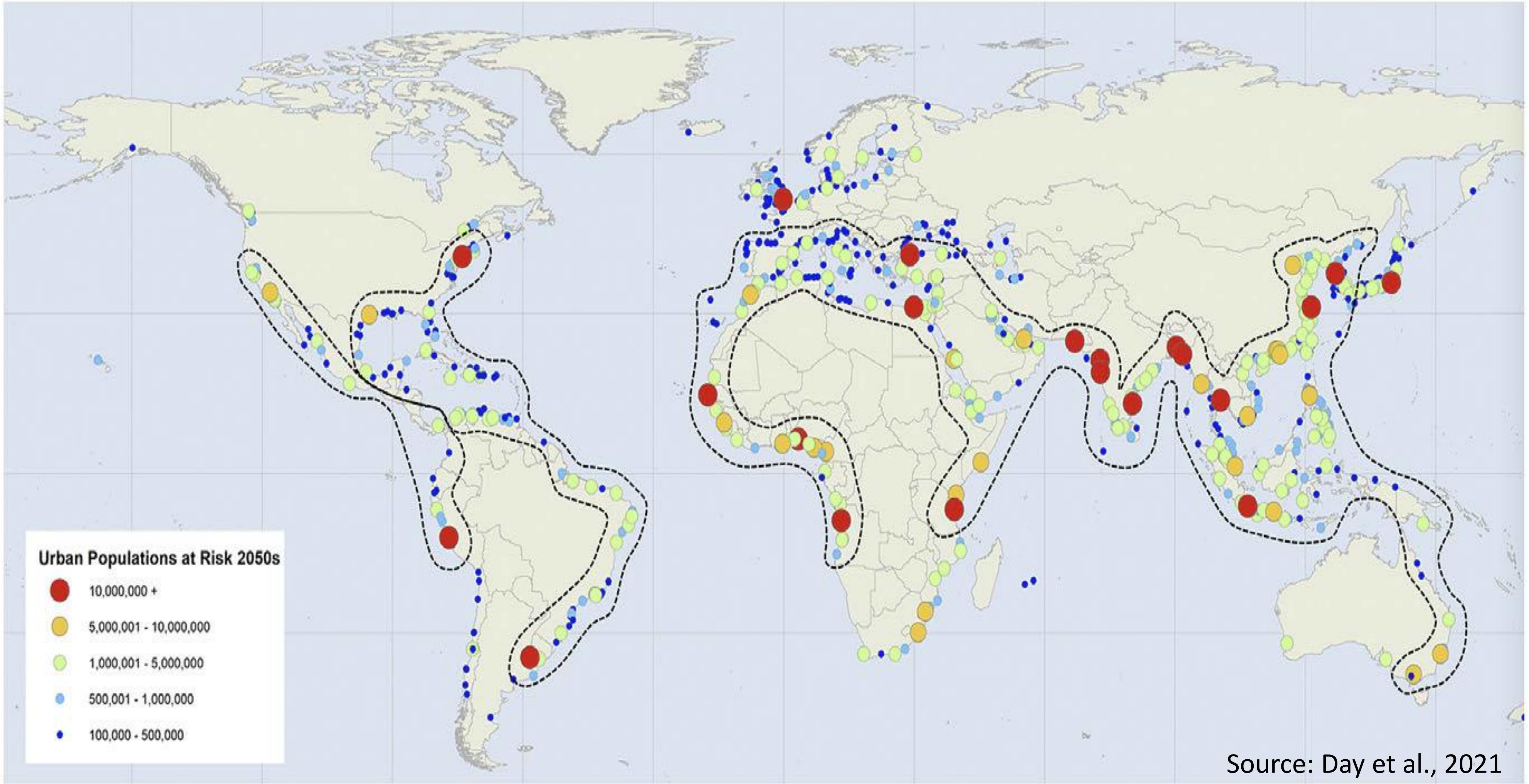
Loss of biodiversity and ecosystem services
Coastal pollution
Eutrophication
Habitat degradation

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**.

We have to deal with coastal hazard!!!!

Effects of Climate Change

Climate change will deeply affect the global coastal area



Source: Day et al., 2021

Coastal zones are at the **forefront** of areas threatened by **climate change** in terms of direct impacts due to warming of the atmosphere and oceans, accelerated sea level rise, larger and more intense tropical cyclones, extreme precipitation events, and changes in river discharge and especially given the intense development there (Day et al., 2023).

The Coastal Digital Twin of the Ocean...

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

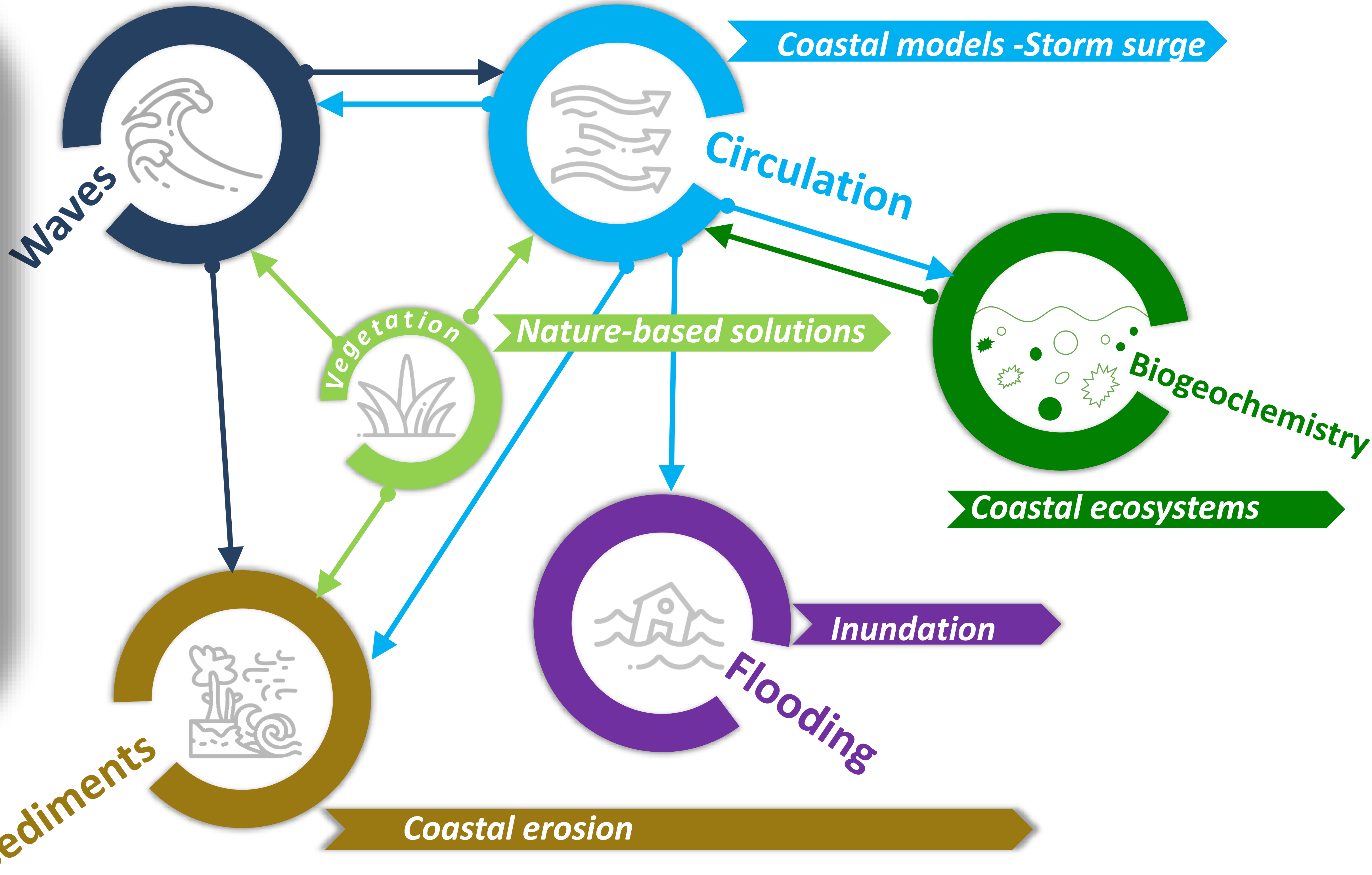
Combining **modeling** and **observational data,** and elements of **AI**

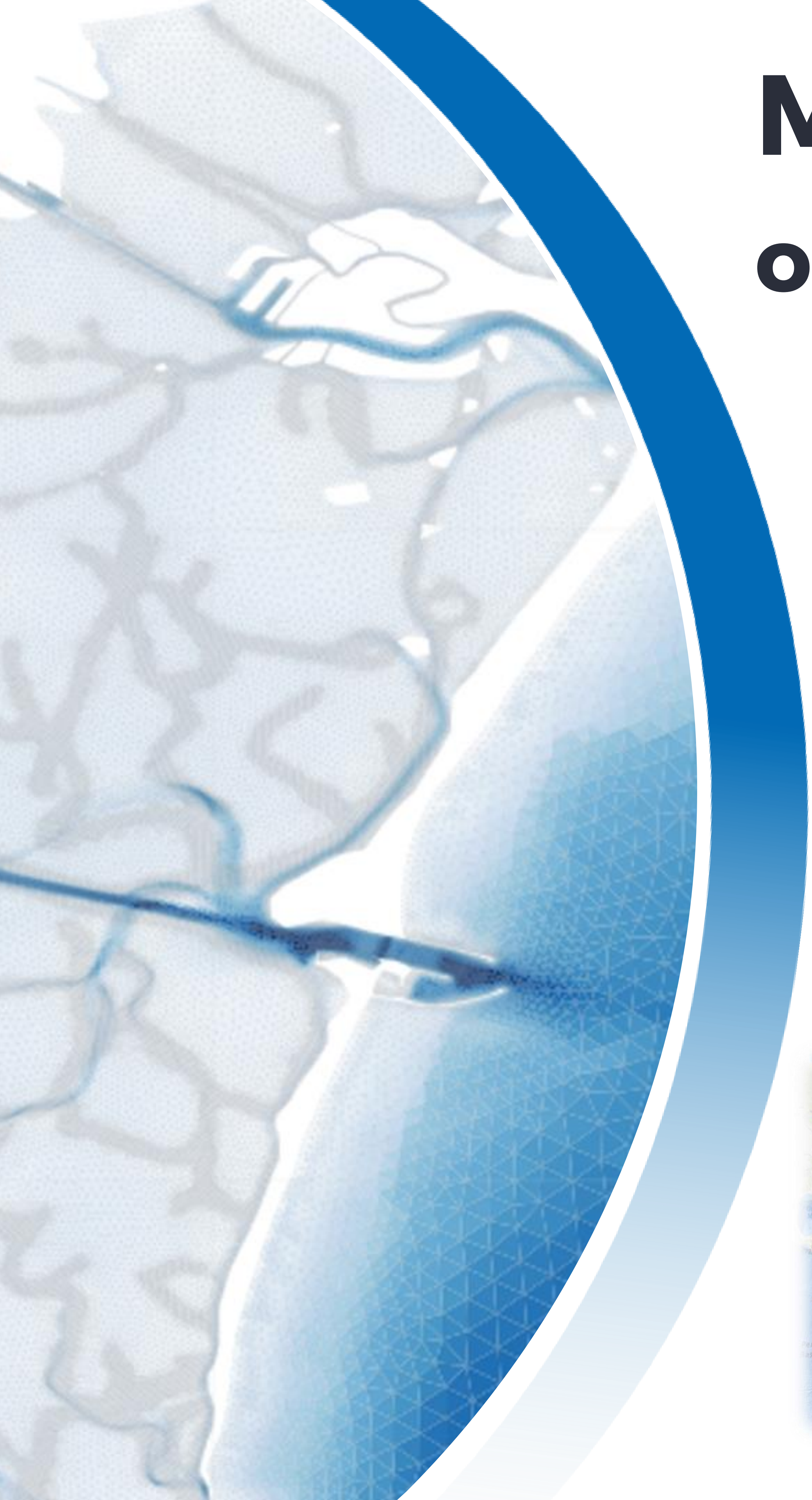
Designed for **end-user usability**

"What-if" scenarios

Capacity for **relocability**

A digital representation of physical reality using models and data





Marine 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

20+ implementation over the world

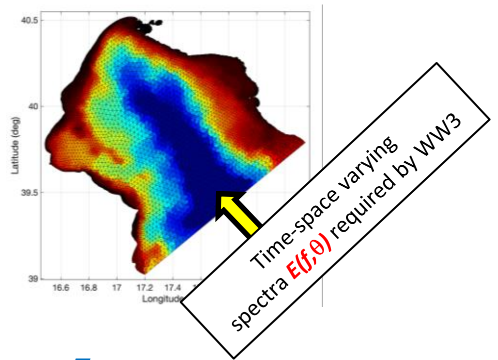
Easy deployment and relocability

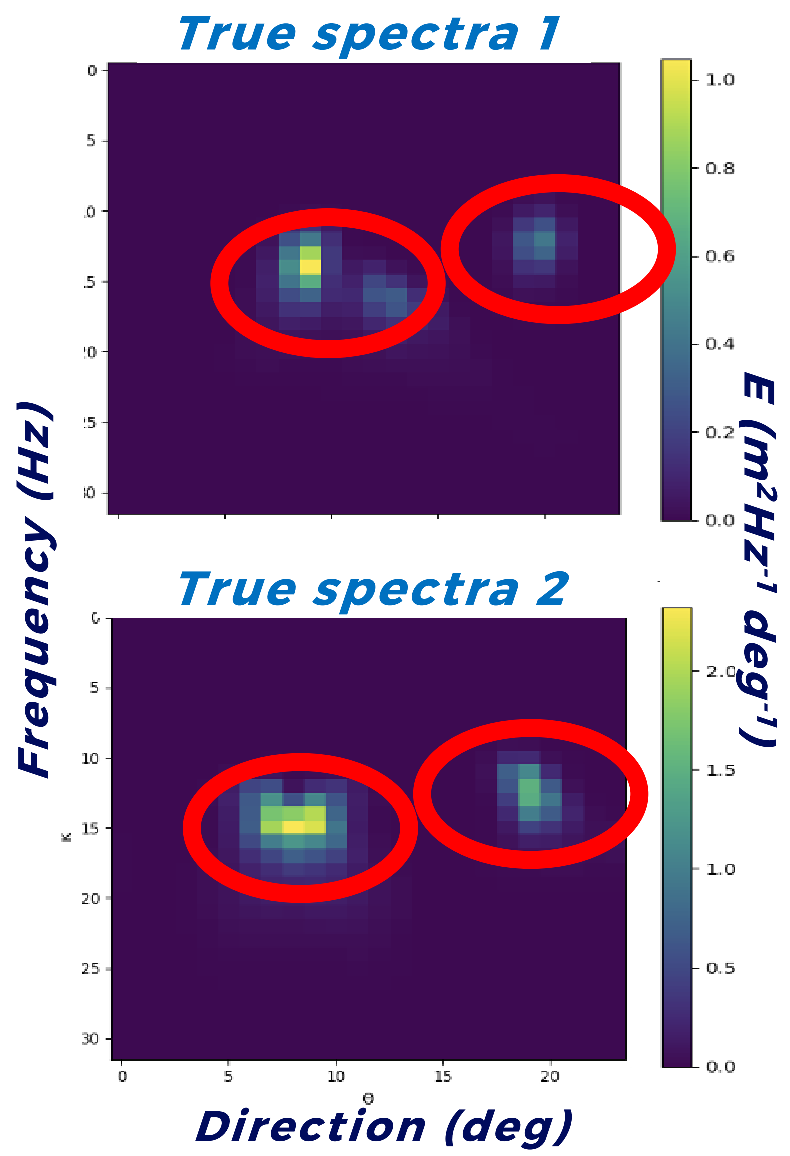
Cross-scale Operational forecasting or hindcast for event-based approach

Port and oil-spill applications, Strait dynamics, Urban ocean, Storm surge

Improving downscaling

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



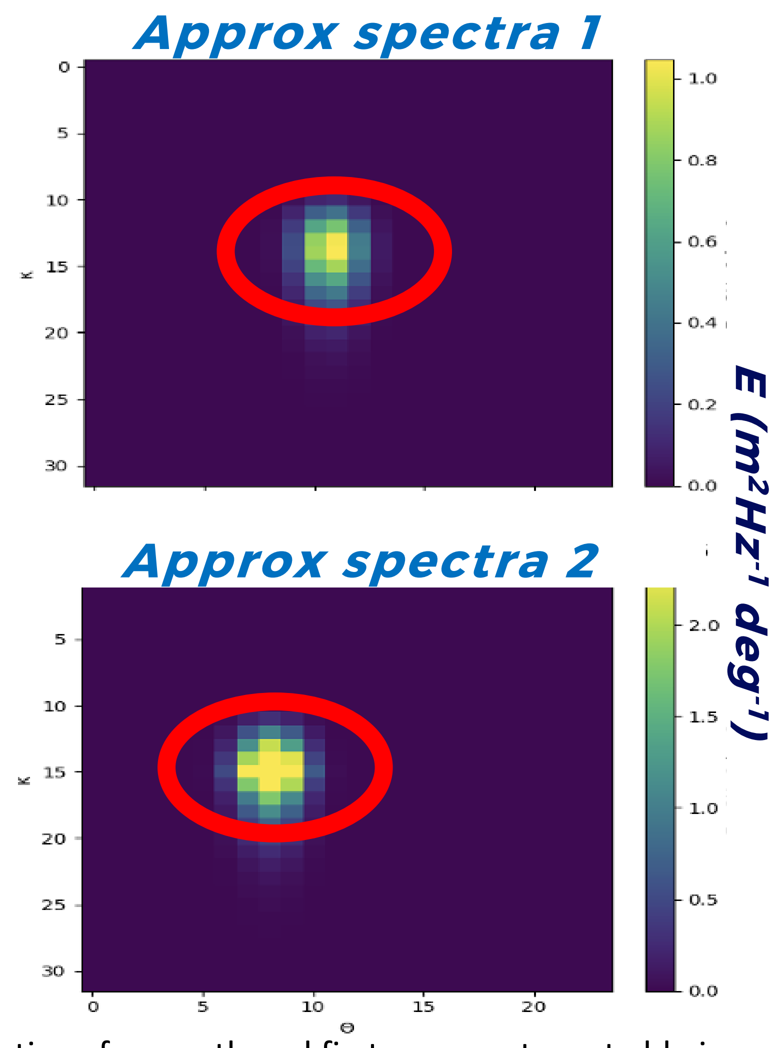


Real spectra

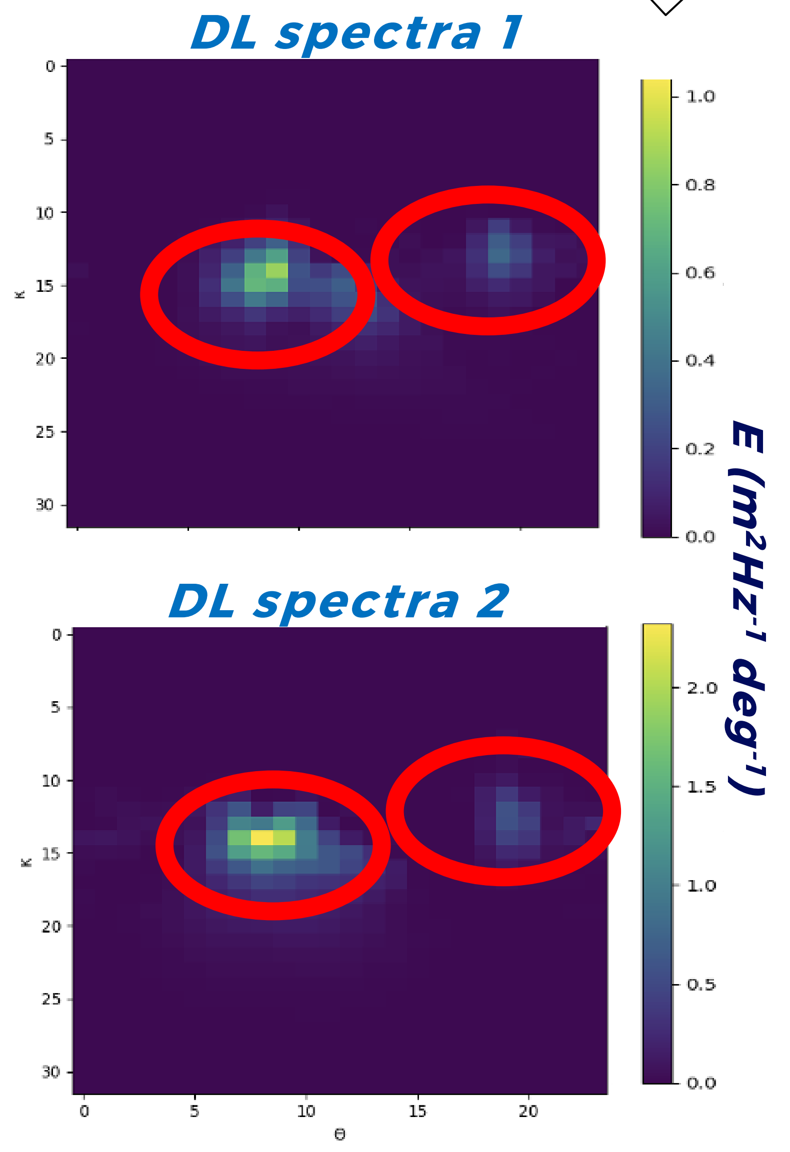
Wave model need wave energy spectra at the open lateral boundary.
High-storage cost, very low availability

Traditional solution

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



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

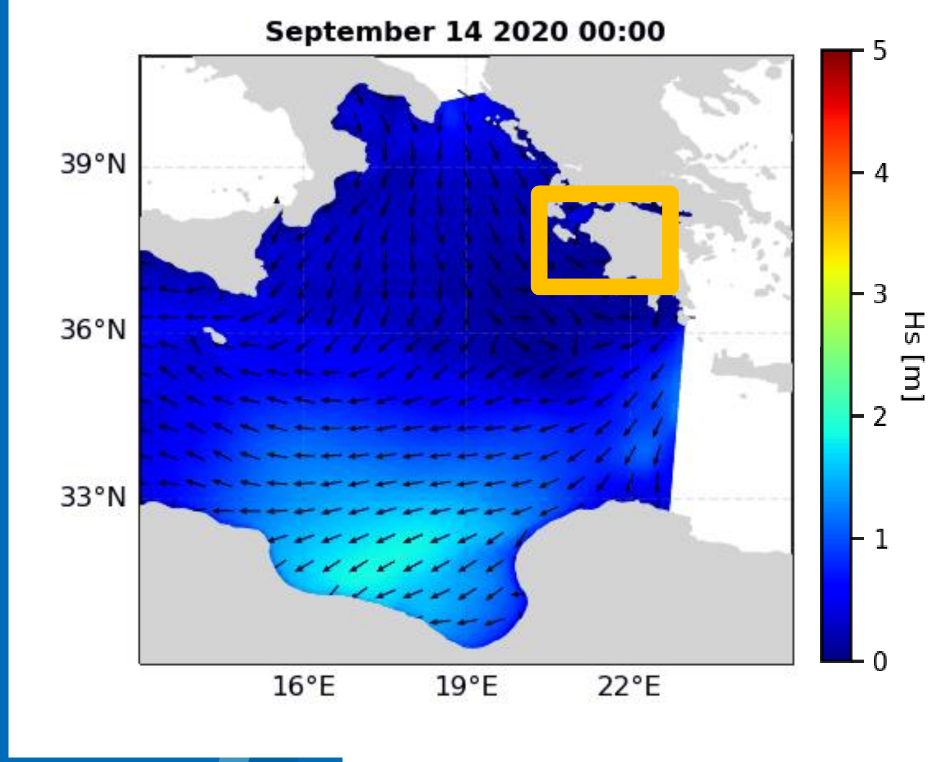


Innovative and **integrated** solution

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

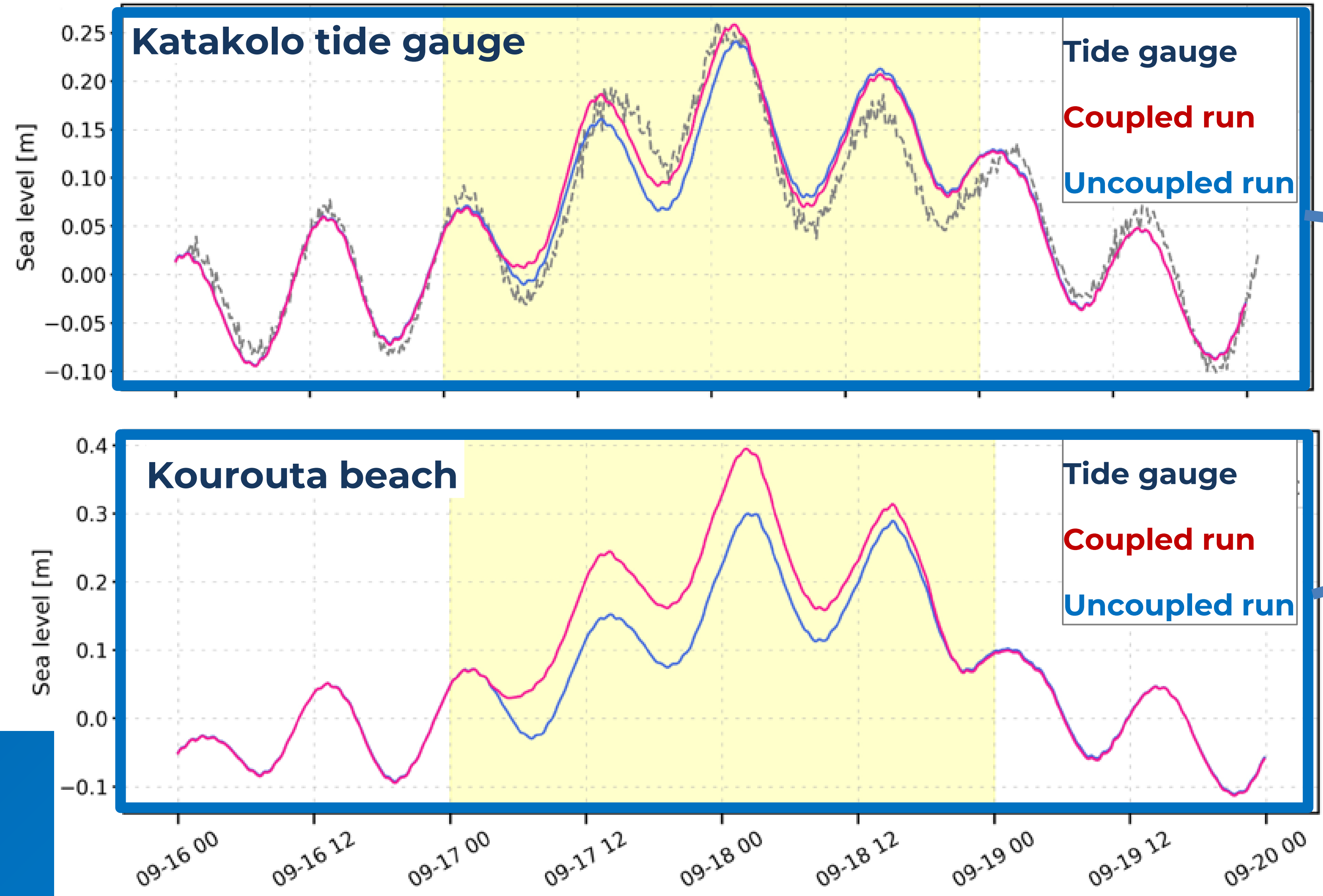
Storm surge: wave-currents interaction

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



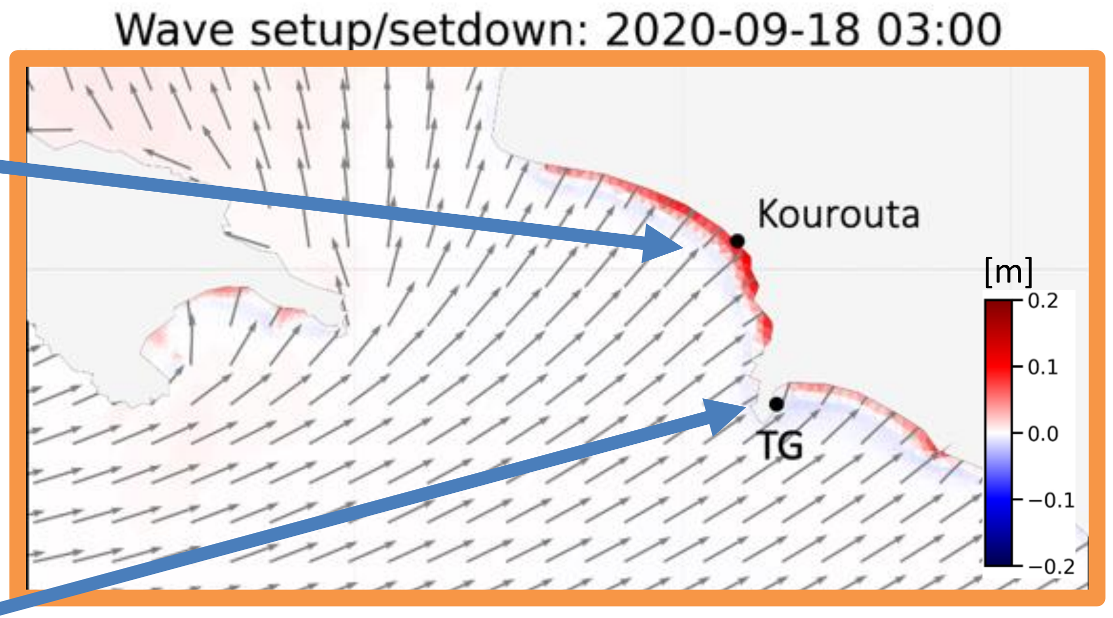
Medicane *Ianos*, 2020

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 model accuracy in describing the event.
In the bottom panel, the model configurations are compared at the Kourouta beach.



Wave setup and setdown

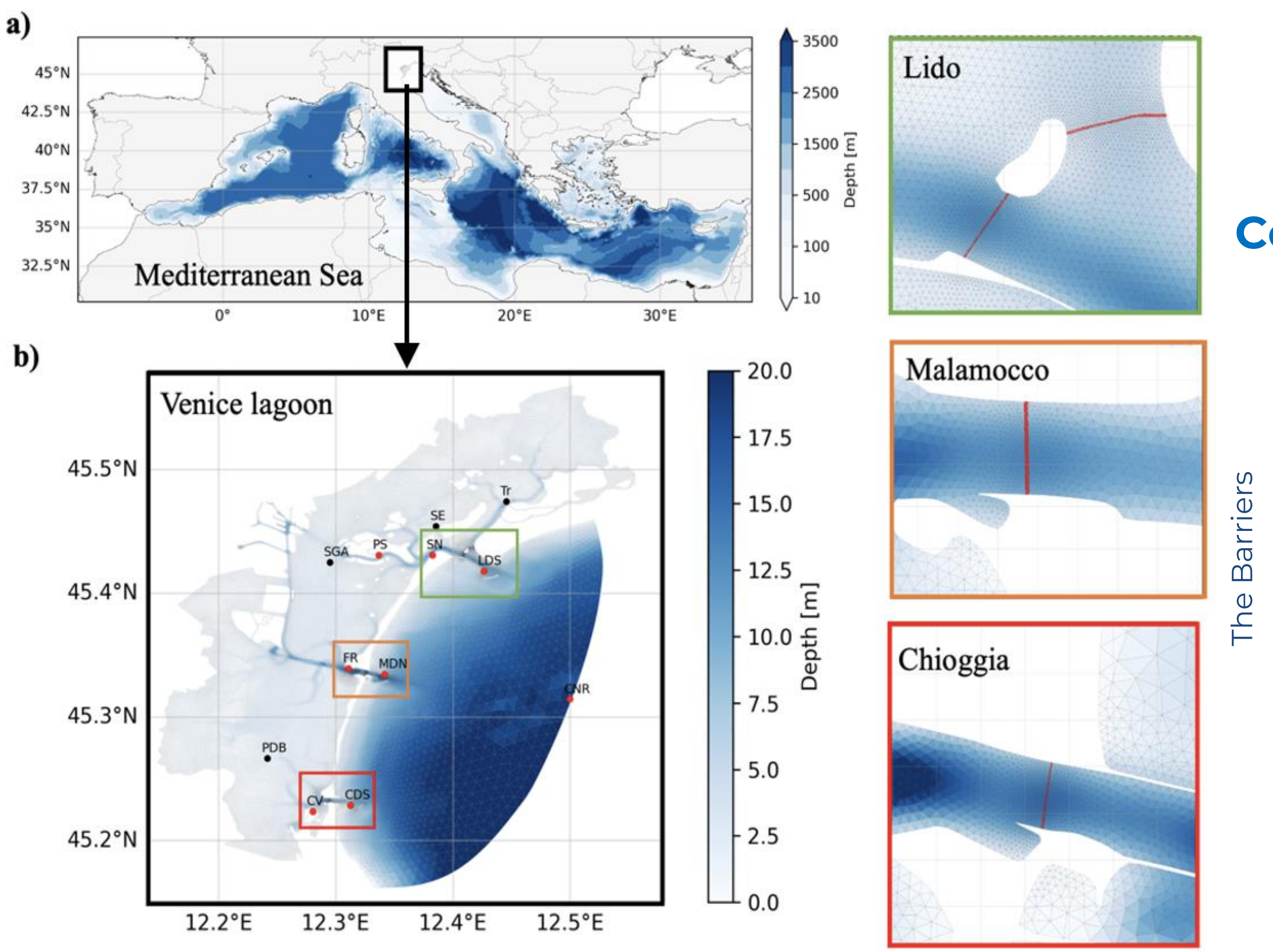
TWL difference between free and coupled runs. Vectors show the mean wave direction. The variability of TWL, considering the wave contribution, could reach 30%.

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 [preprint]**, https://doi.org/10.5194/egusphere-2024-3517, 2024.

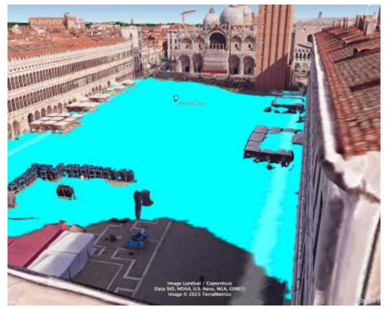
Flooding: downstream MODELS from circulation and WHAT-IF SCENARIOS

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.

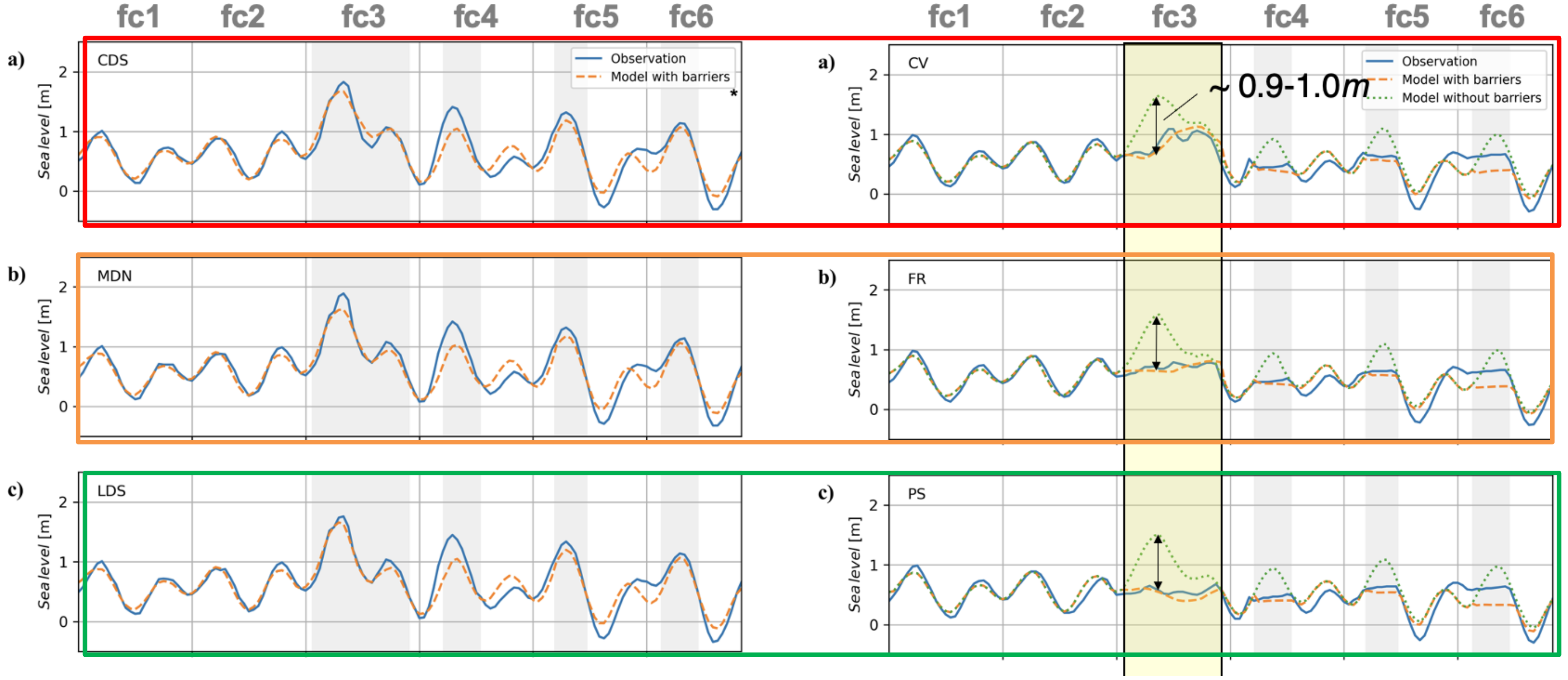
The Venice Lagoon and the MoSE



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



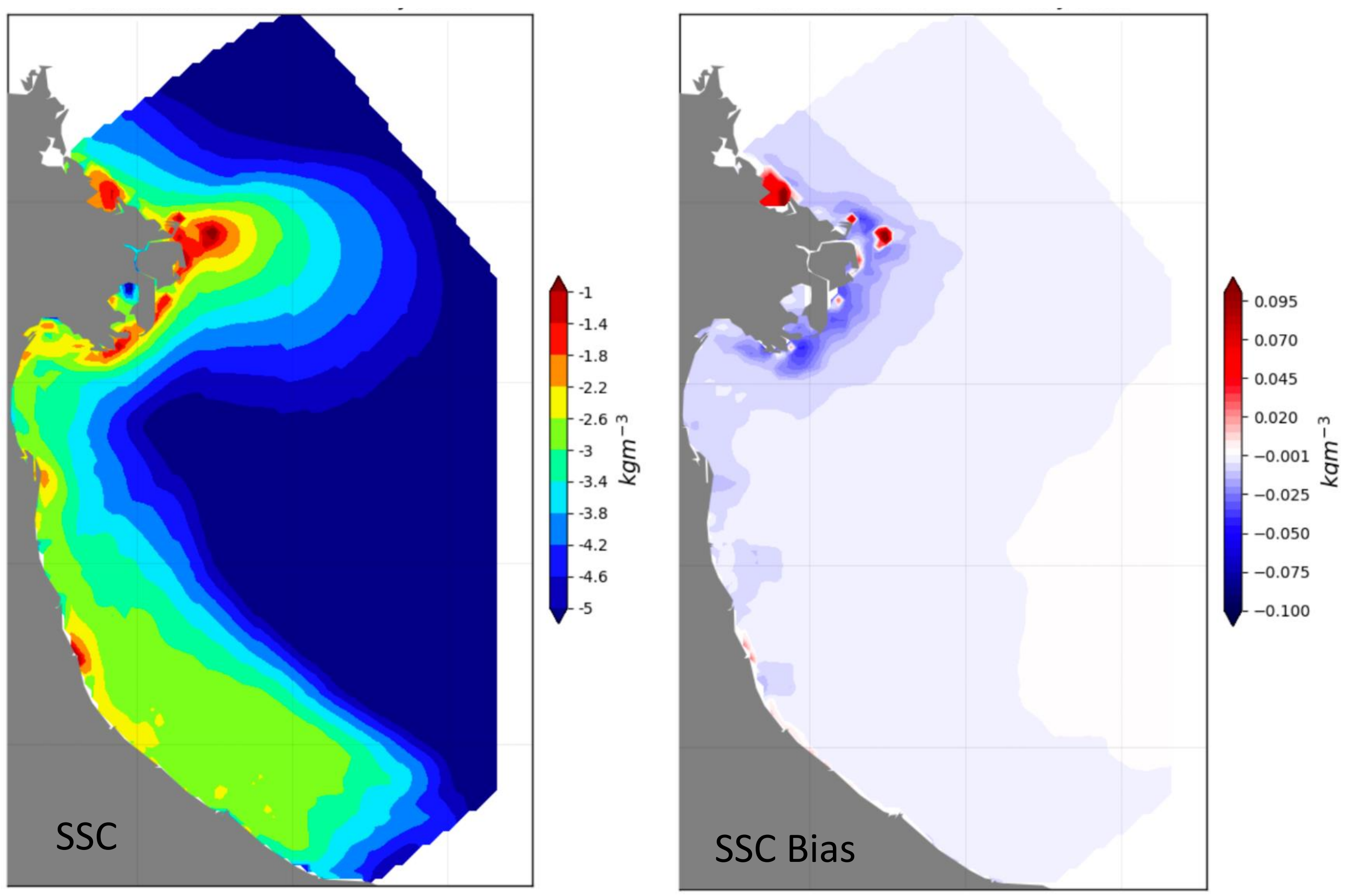
Comparison with Tide gauge during The "Acqua Alta" event of Nov. 2022



Coastal erosion

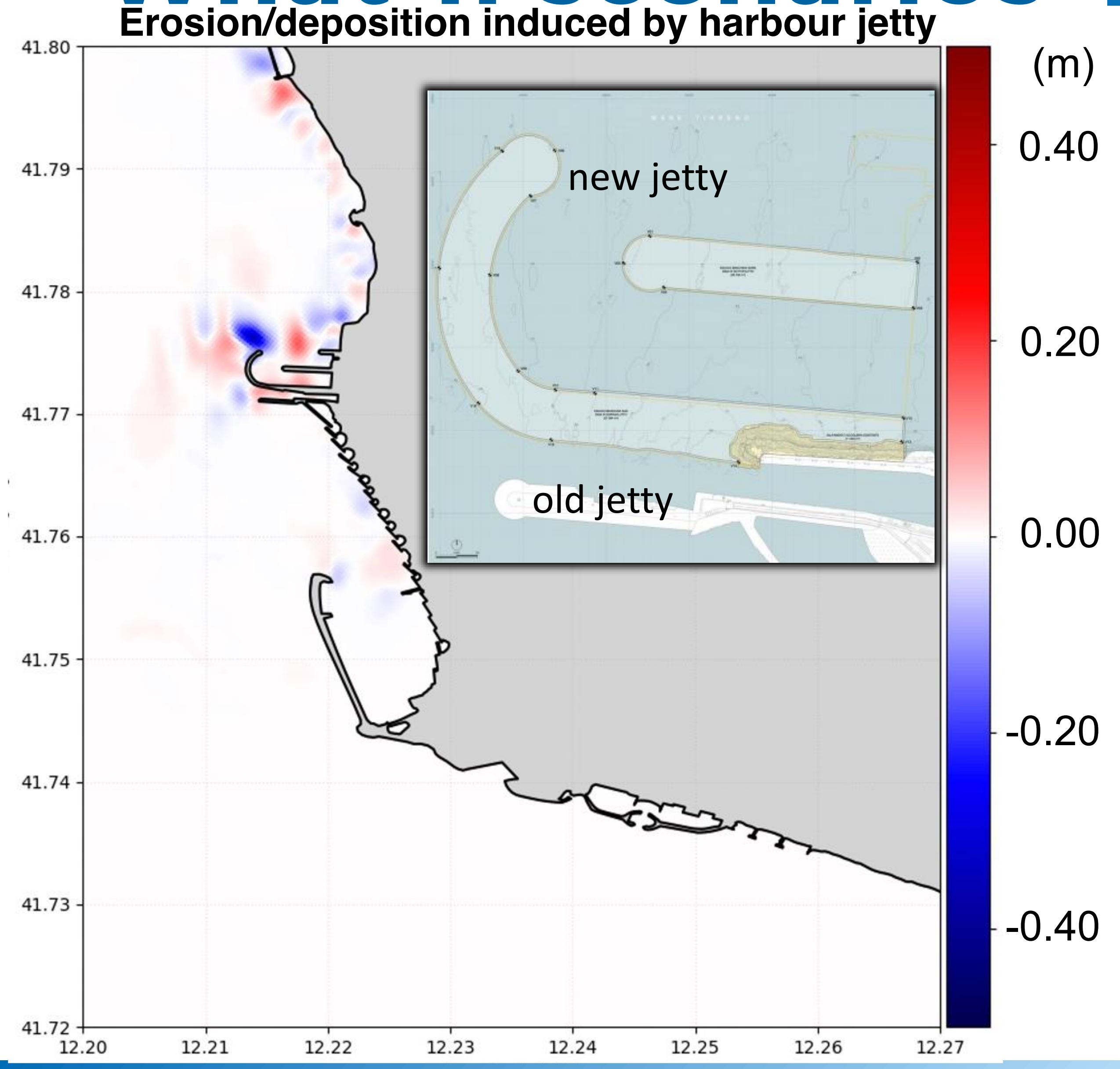
Integration of **sediment transport** module in the coupled modelling framework

Model — Satellite



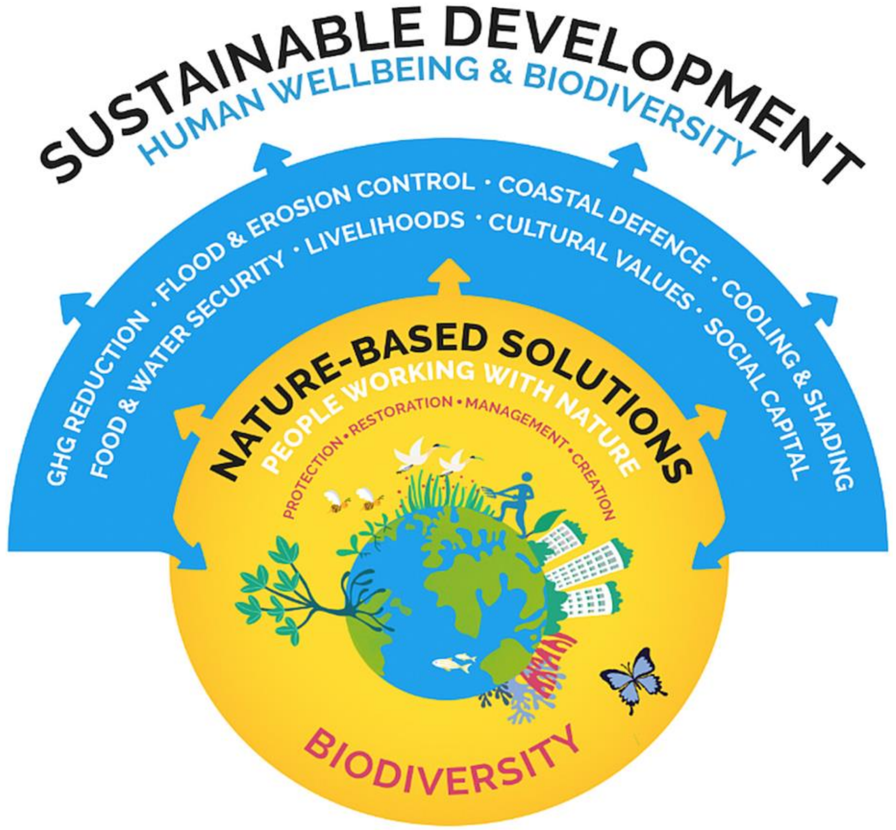
Sediment Suspended Concentration for Emilia Romagna [Kg/m3]

What-if scenarios



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

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



NBS Seagrass

Ecosystem services

HABITAT CORRIDOR
BIODIVERSITY
NURSERY AREA
FOOD

OXYGEN
CARBON STORAGE
NUTRIENT CYCLING
WATER QUALITY

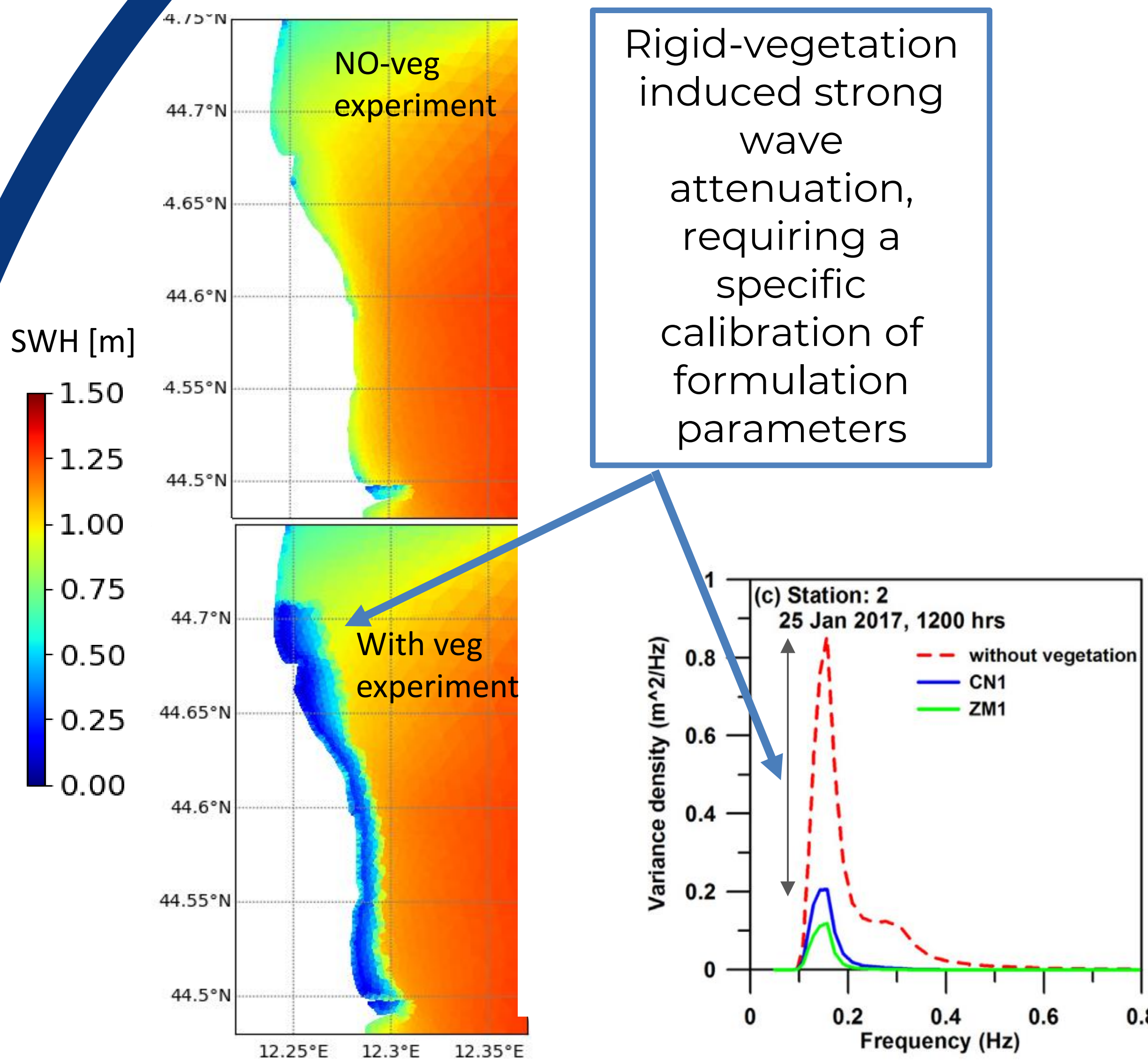
COASTAL PROTECTION
SEDIMENT STABILIZATION
WAVE DAMPING
CURRENTS DAMPING
SEDIMENT TRAPPING

Advancement with seagrass

Rigid vegetation

First implementation of vegetation in wave and circulation models, with **rigid approach**.

Emilia Romagna



Pillai, Umesh Pranavam Ayyappan, et al. "A Digital Twin modelling framework for the assessment of seagrass Nature Based Solutions against storm surges." *Science of the Total Environment* 847 (2022): 157603.

Advancement with seagrass

Rigid vegetation

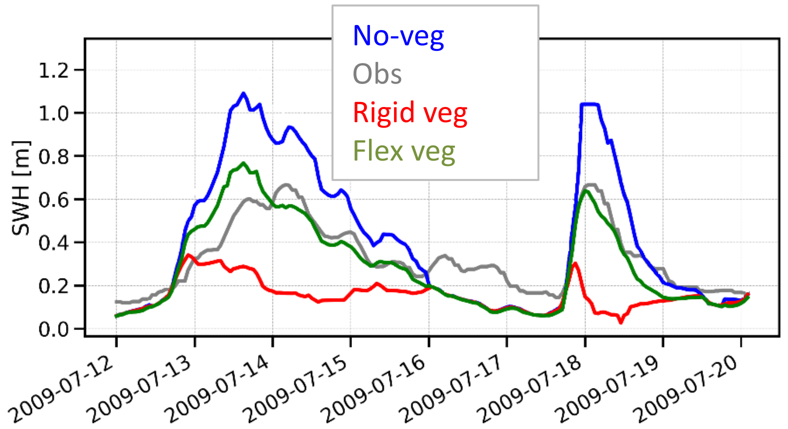
First implementation of vegetation in wave and circulation models, with **rigid approach.**

Flexible vegetation

Evolution of the vegetation physics towards **flexible leaves** which improved significantly model performances.

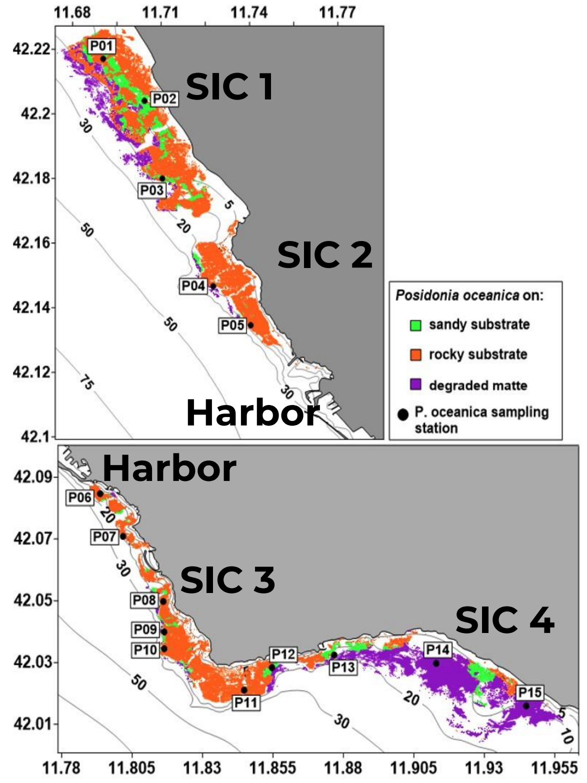
Validation

flexible vegetation physics vs Idealized testcases based on *Infantes et al.,2012*



Application at Civitavecchia SICs

Four SICs surround the harbor of Civitavecchia. Measurement surveys identified three populations of ***Posidonia oceanica***. These populations are distinguishable by their phenotypic traits, which have developed in response to growth on **sandy, rocky, or dead-matte substrates.**



For a realistic implementation of the vegetation in the area, we included all three populations, enabling **differentiation in wave attenuation across the SICs.**

Wave attenuation at SICs

Advancement with seagrass

Rigid vegetation

First implementation of vegetation in wave and circulation models, with **rigid approach.**

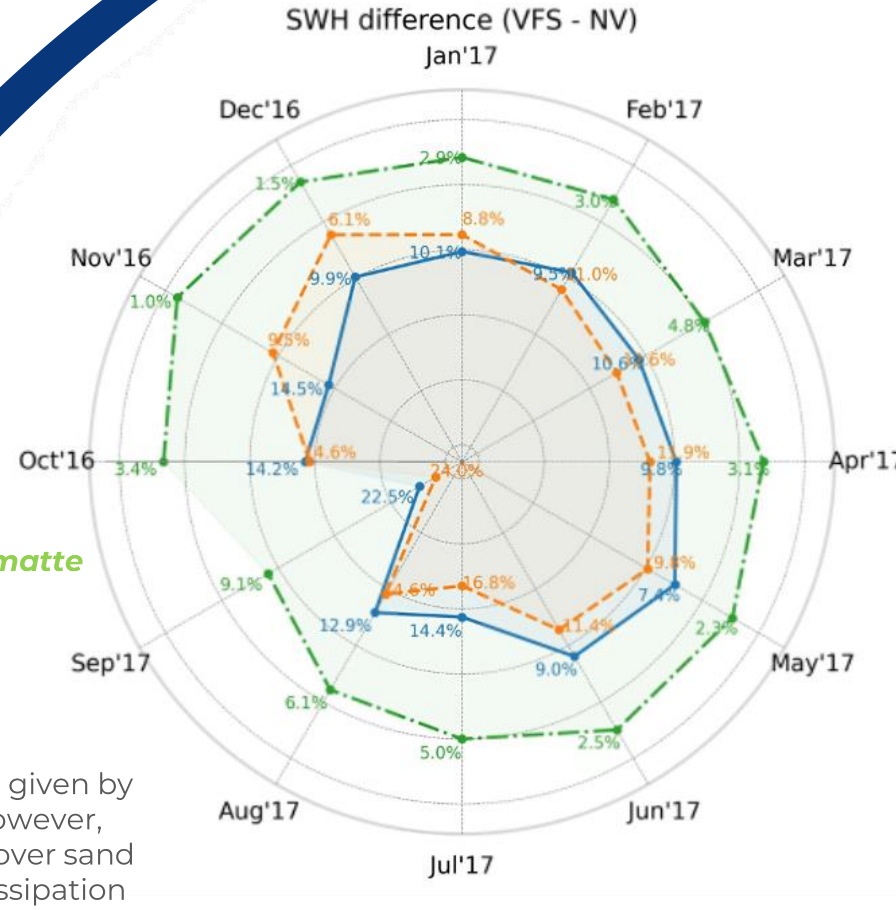
Flexible vegetation

Evolution of the vegetation physics towards **flexible leaves** which improved significantly model performances.

Seasonal growth cycle

Evolution of seagrass representation: inclusion of **seasonal growth cycle** based on **in-situ measurements**.

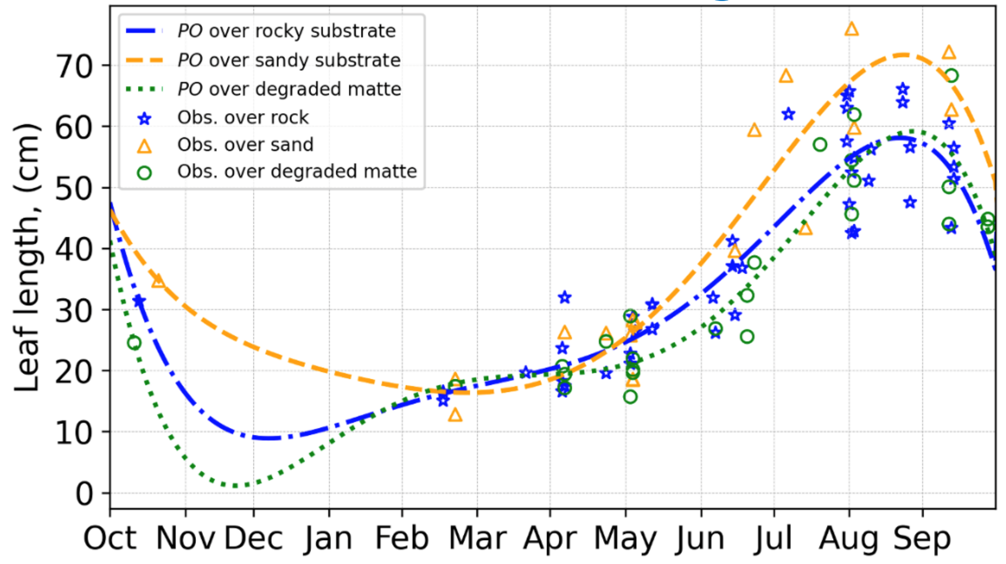
Seasonal wave attenuation



PO over rock
PO over dead matte
PO over sand

Higher dissipation given by PO over rock. However, during winter PO over sand showed higher dissipation

Seasonal leaf length

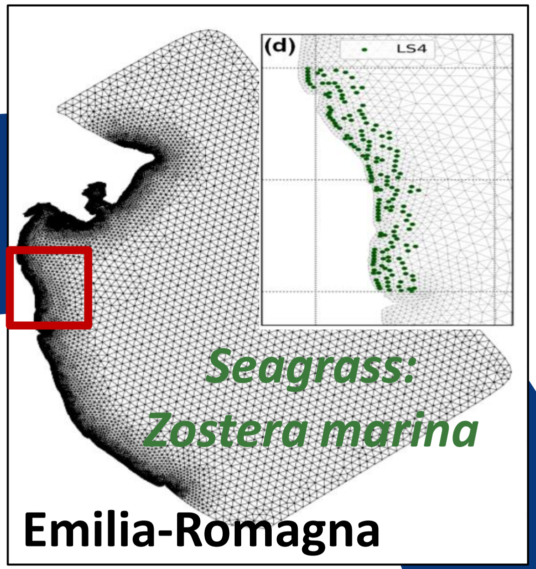


PO: *Posidonia oceanica*

What-If Scenarios: Seagrass variability

Ensemble Simulations

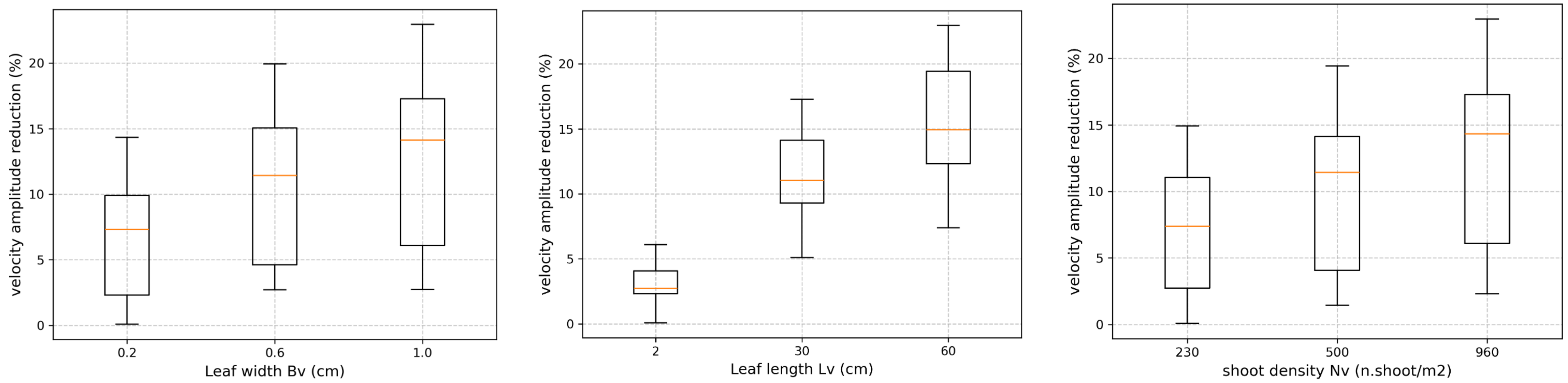
What-If Scenarios		L_v (cm)		
N_v (n. shoot / m²)	b_v (cm)	2	30	60
230	0.2	*WiS-1*	*WiS-10*	*WiS-19*
	0.6	*WiS-2*	*WiS-11*	*WiS-20*
	1.0	*WiS-3*	*WiS-12*	*WiS-21*
500	0.2	*WiS-4*	*WiS-13*	*WiS-22*
	0.6	*WiS-5*	*WiS-14*	*WiS-23*
	1.0	*WiS-6*	*WiS-15*	*WiS-24*
960	0.2	*WiS-7*	*WiS-16*	*WiS-25*
	0.6	*WiS-8*	*WiS-17*	*WiS-26*
	1.0	*WiS-9*	*WiS-18*	*WiS-27*

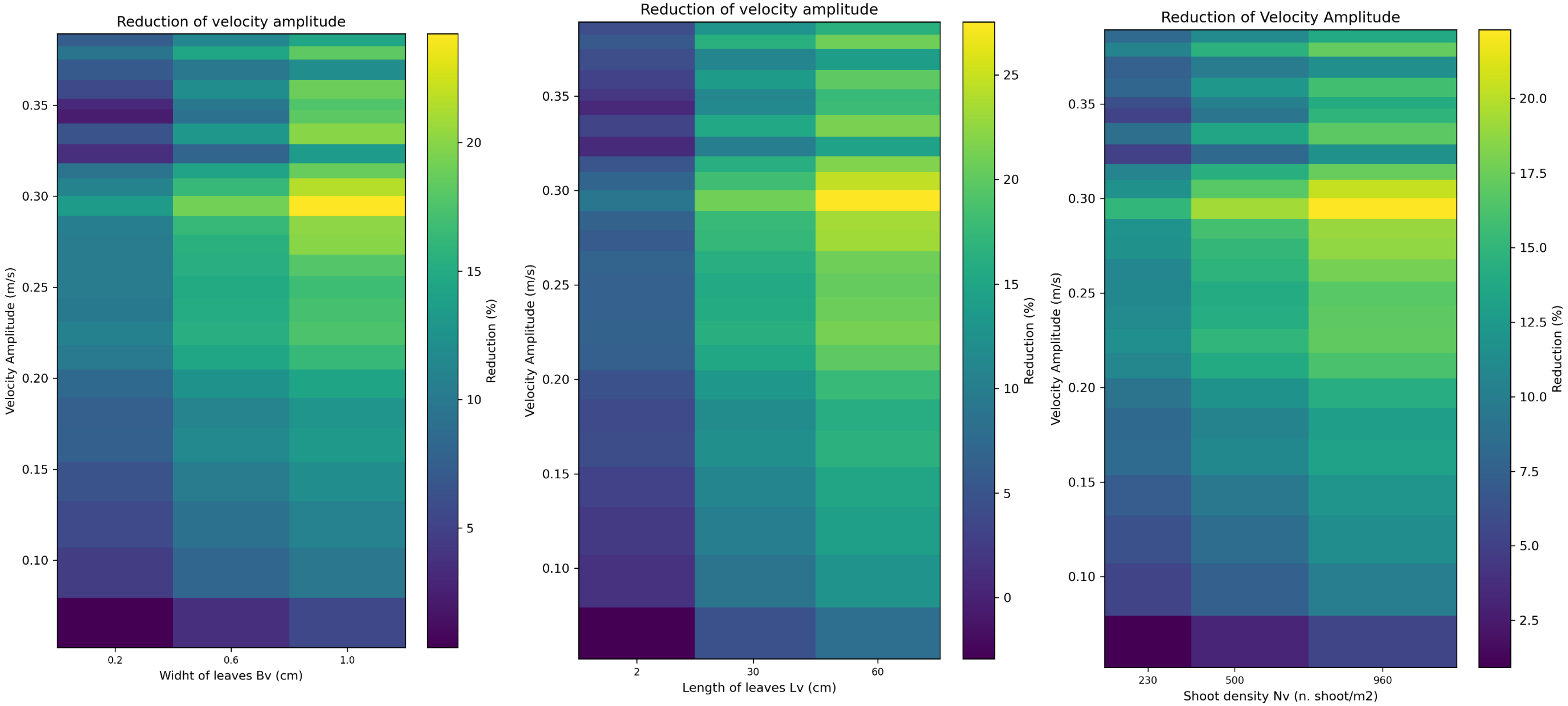


Seagrass characteristics

- **Lv ->** Leaf length
- **Bv ->** Leaf width
- **Nv ->** Seagrass density

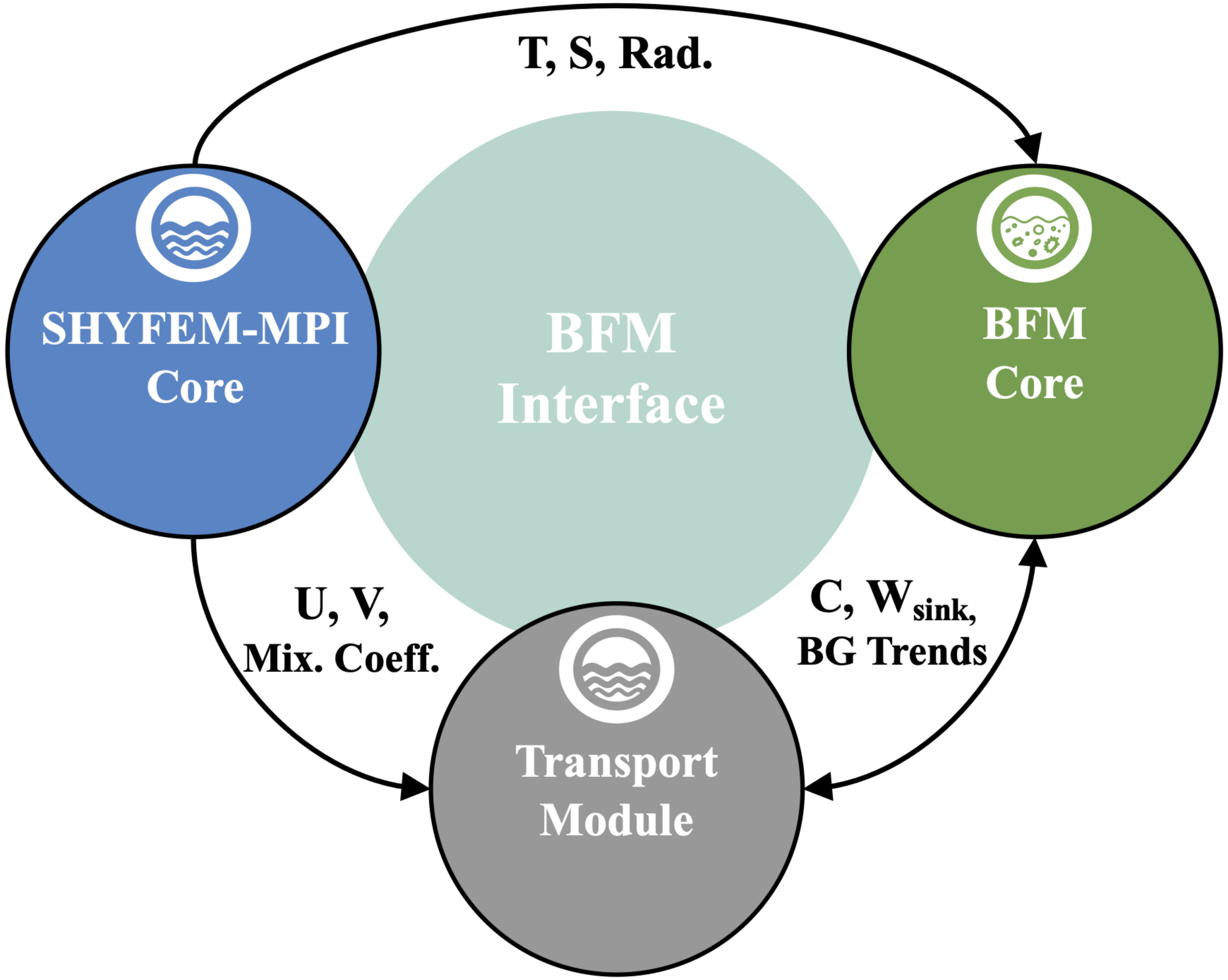
Current amplitude attenuation





Coastal Ecosystems

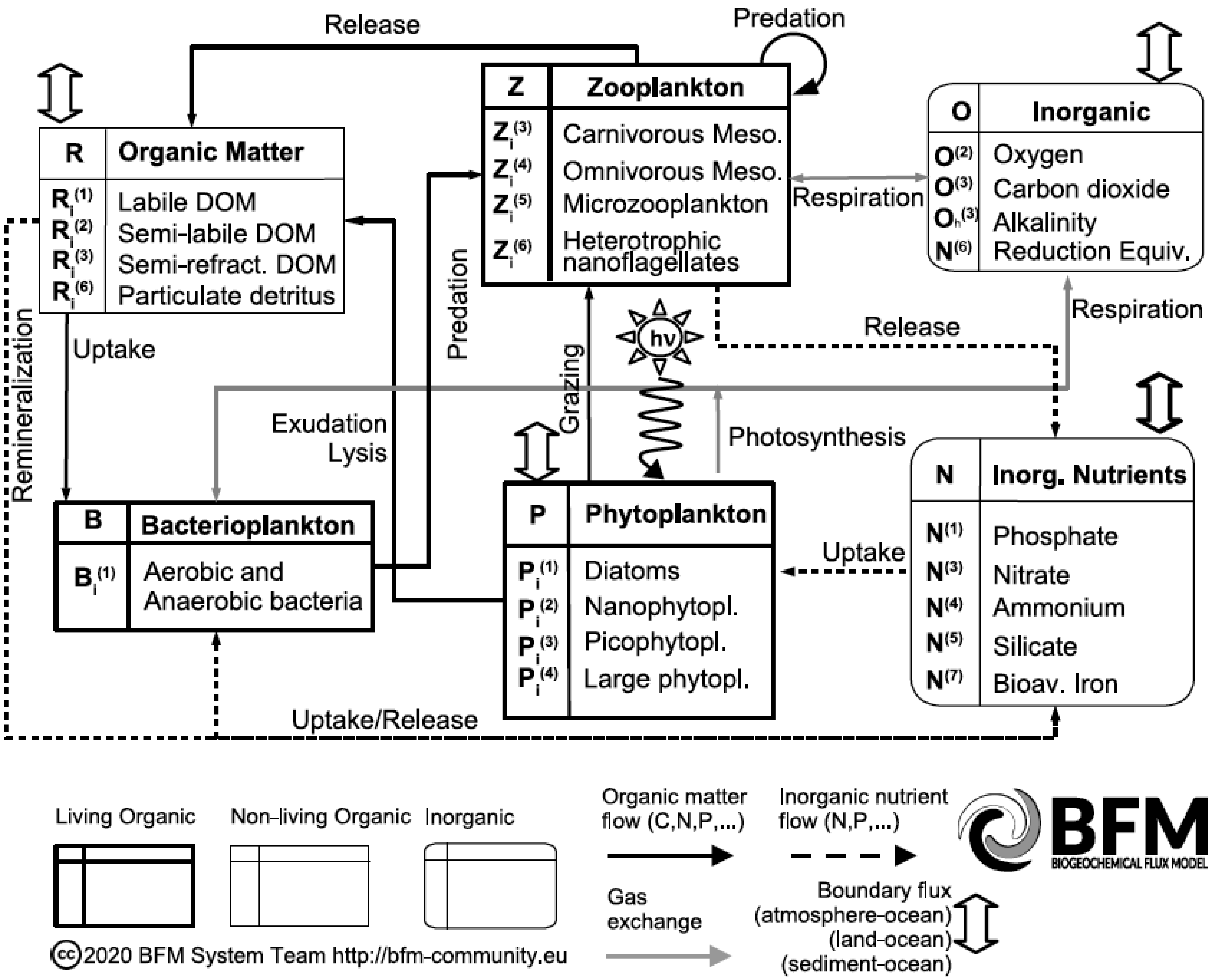
Coupling unstructured ocean circulation model with Biogeochemistry to enhance coastal ecosystem representation



Coastal Ecosystems

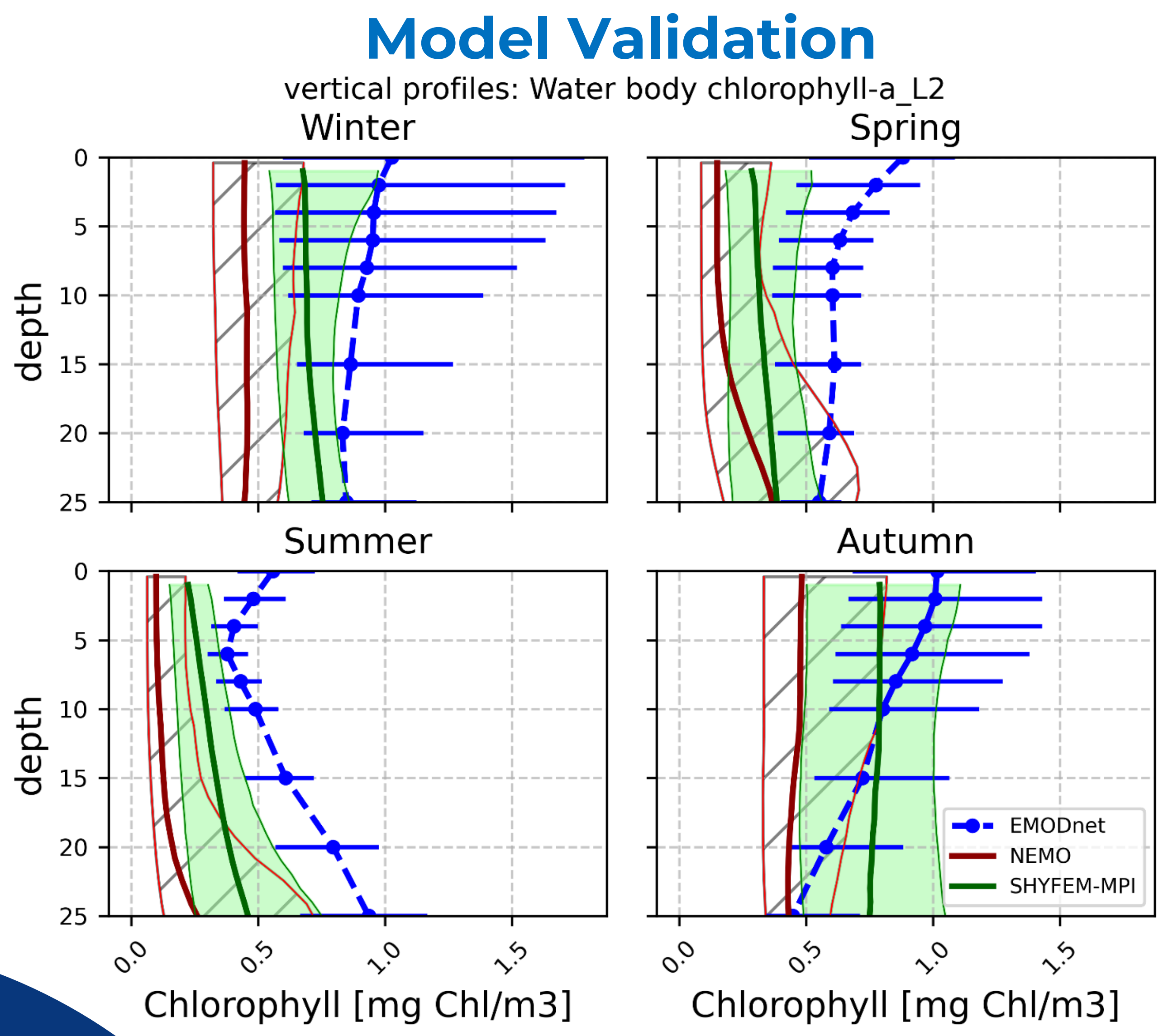
The biogeochemical model

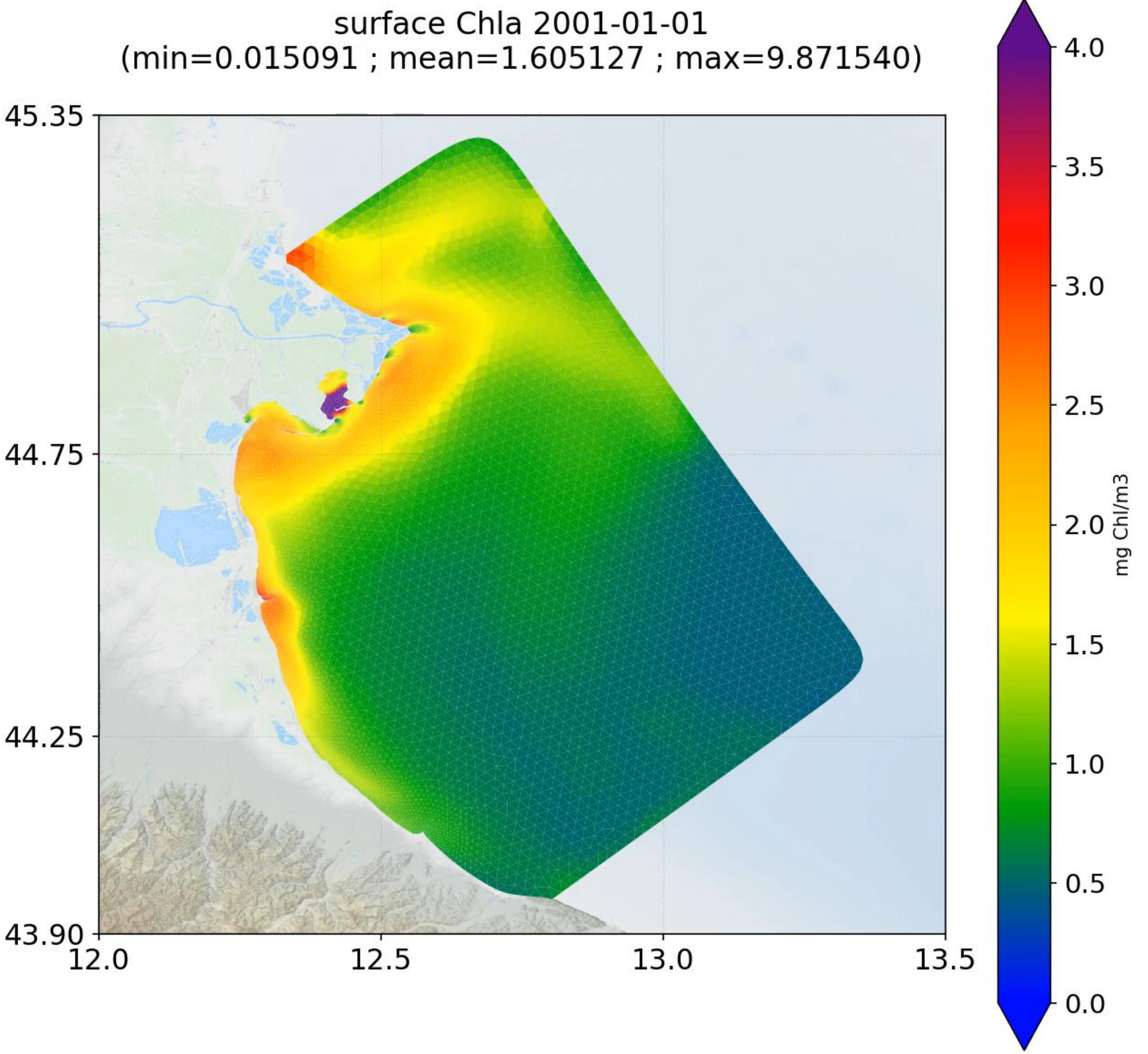
The **BFM** (Biogeochemical Flux Model V. 5.2; Vichi et al., 2020) is an open-source community model based on the living and non-living Functional Groups (FG) approach capable of reproducing the main features of the pelagic and benthic lower trophic layers and biogeochemical cycles.



Coastal Ecosystems

Importance of plume representation in coastal ecosystems with high river discharge





Conclusions

The Coastal Digital Twin of the Ocean

What are the main components? Models, Observations, AI, end-user orientation

Further development: Improving the AI contribution: Sediment and Vegetation

Further development: Improving the integration and interaction between components and usability

Thanks!

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