COASTAL RESILIENCE SCHOOL

Sustainable Coastal Growth and Resilience

Lesson: Assessing Nature Based Solutions with a Digital Twin of the Ocean

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Period: 18th March 2025

unesco Intergovernmental Oceanographic Commission

UN Decade Collaborative Centre for COASTAL RESILIENCE

OTGA OceanTeacher Global Academy

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

1. Coastal Environments and Hazard

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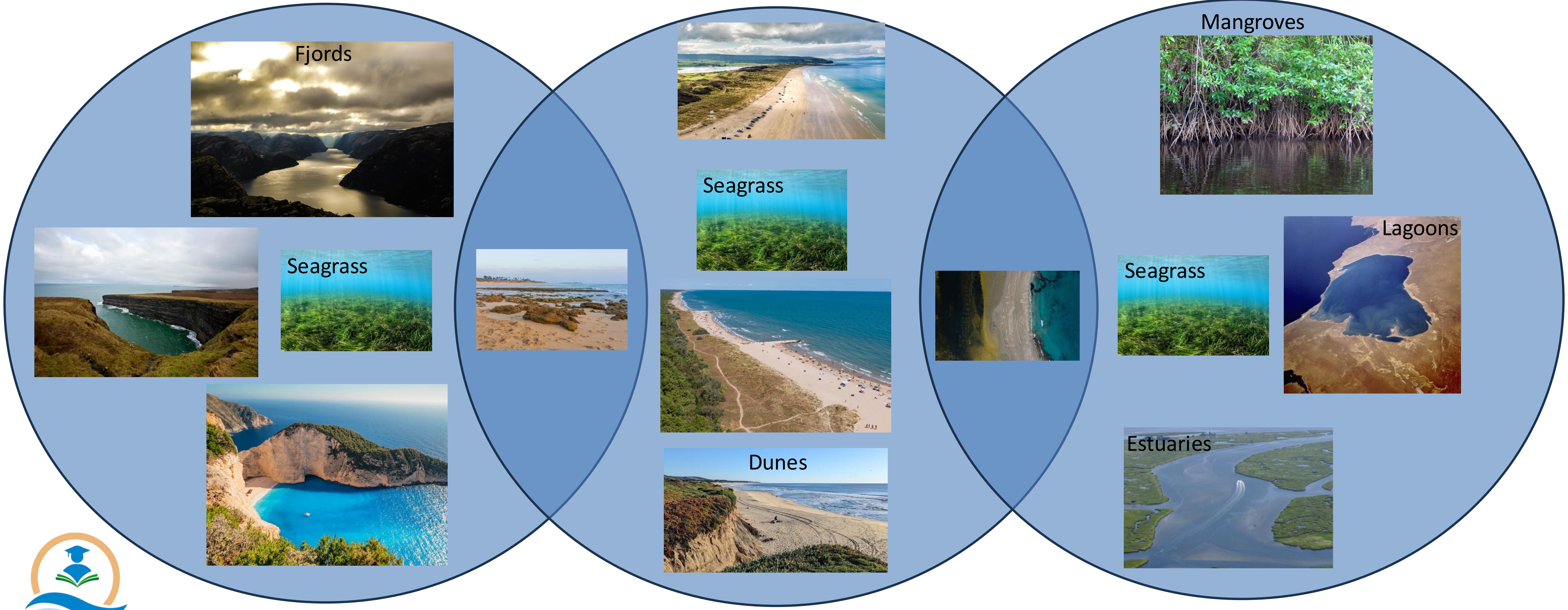
Coastal Environments

The global coastal ocean, a mosaic of different environments...

Rocky Shores | Sandy Beaches | Wetlands



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Credit for seagrass photo:
Dimitris Poursanidis / Ocean Image Bank

...Strongly interconnected

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Coastal Environments

And highly urbanized

- Areas of **high biodiversity**, **biological productivity**, **population growth** and **economic acitivity**.
- **40 %** of the world population lies within **100km** from the **coast**. Mostly in tropical developing country.
- The largest **megacities** in the world are in **coastal areas**.
- **Growth of population** and **economic activity** in coming decades is projected to occurr in **coastal areas**.

Source: Day et al., 2021, 2023

We have to deal with coastal hazard!!!!

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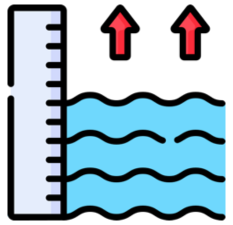
Coastal Hazard

Erosion and Coastal Retreat

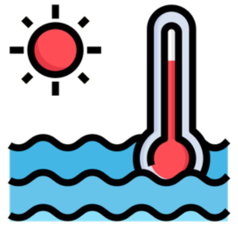
Storm Surge and Coastal Flooding



Sea level rise

Saltwater Intrusion

Coastal Pollution



Marine Heatwaves

And many other related problems!

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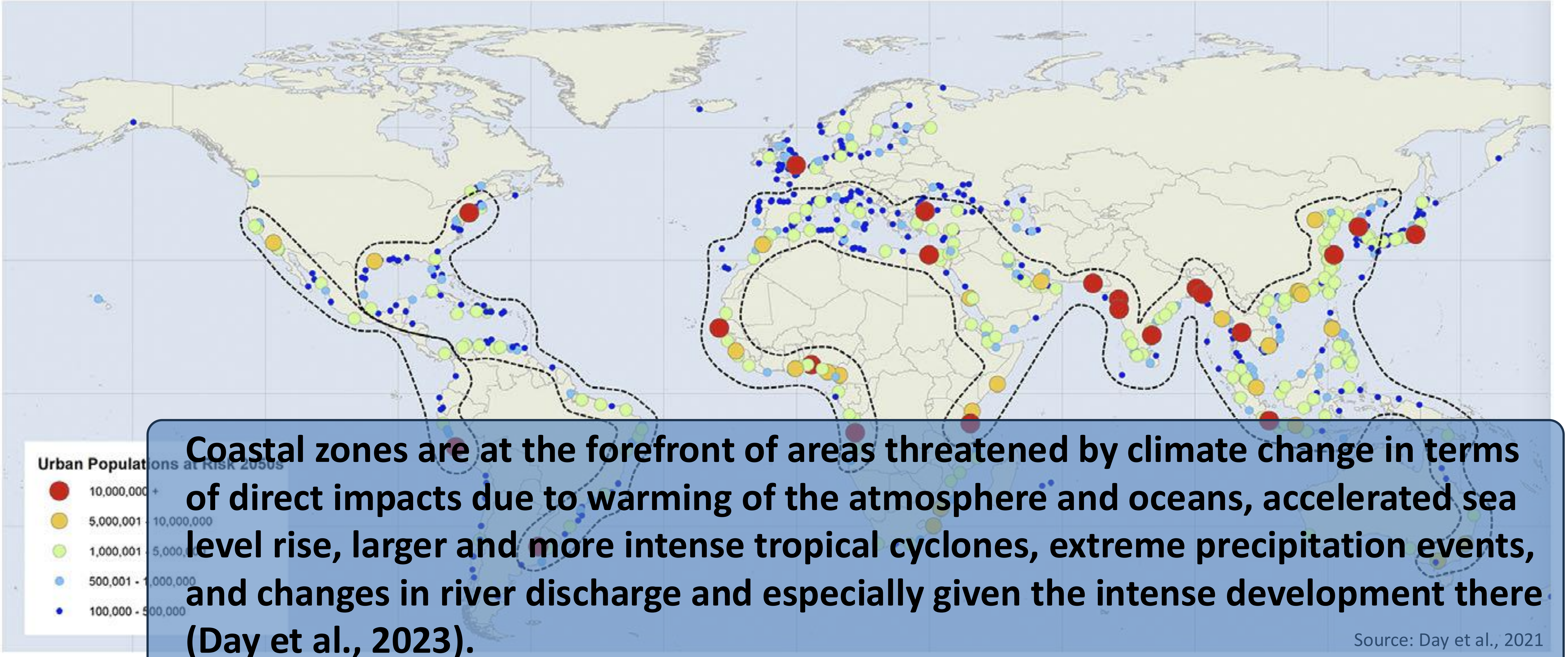
Images source: Flaticon.com

Effects of Climate Change

Climate change will deeply affect the global coastal area



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).

Source: Day et al., 2021

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Storm Surges

- Coastal flooding is a combination of high tides, storm surge and severe wave conditions. During extreme events, currents, tides combine with waves to severly erode beaches.

- During the period 1970-2019 storm surge related to tropical cyclones have caused death of up to 962000 people and cost of nearly USD 1600 bilion (Kunz and Stroble, 2024).

- 1.5 million people are affected annually by storm surge events, with more than 40% of major events that occurred in South and South-East Asia (Bower and Jonkman, 2018).

- The reduction of coastal hazard should be a primary objective in the planning of future strategy of coastal management, with the development of early warning systems and innovative solutions (*e.g.* **Nature based Solutions)** with the aim of building a **sustainable** and **resilient coast.**

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2. Nature Based Solutions (NBSs)

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What are Nature Based Solutions?

"actions to protect, sustainably manage, and restore natural and modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits" (IUCN, 2016).

Five Key Points of NbS (Louarn et al., 2025)

1. Address specific societal challenges
2. Benefits for biodiversity
3. Benefits for human societies
4. Multifunctional
5. Stakeholders involvement

How this definition applies to storm surge and coastal flooding hazard???

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NBS to reduce Coastal Hazard

"Grey" to "green" spectrum of coastal protection

Classic Grey solutions


Seawalls
https://commons.wikimedia.org/w/index.php?curid=2746549


Groynes
https://commons.wikimedia.org/wiki/File:53sitges.jpg


Breakwater
https://commons.wikimedia.org/w/index.php?curid=1541848

Hybrid solutions


Living Shorelines
https://coastalreview.org/2012/07/living-shorelines-the-natural-alternative/

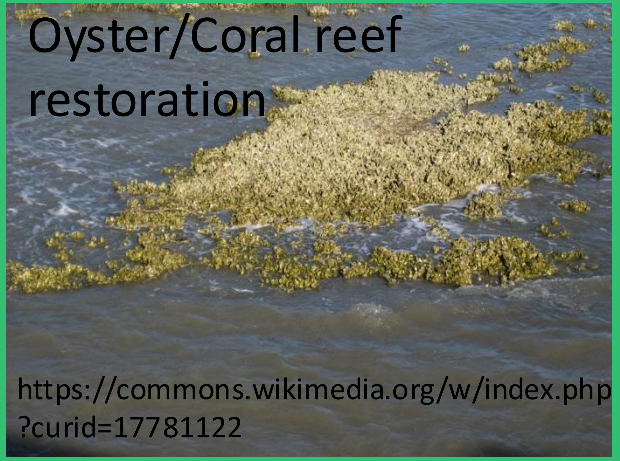

Beach nourishment
https://coastalreview.org/2012/07/living-shorelines-the-natural-alternative/

Dune restoration
https://www.cbc.ca/news/canada/prince-edward-island/pei-dunes-marram-grass-lakeside-beach-1.7330592

Green solutions (NbS)

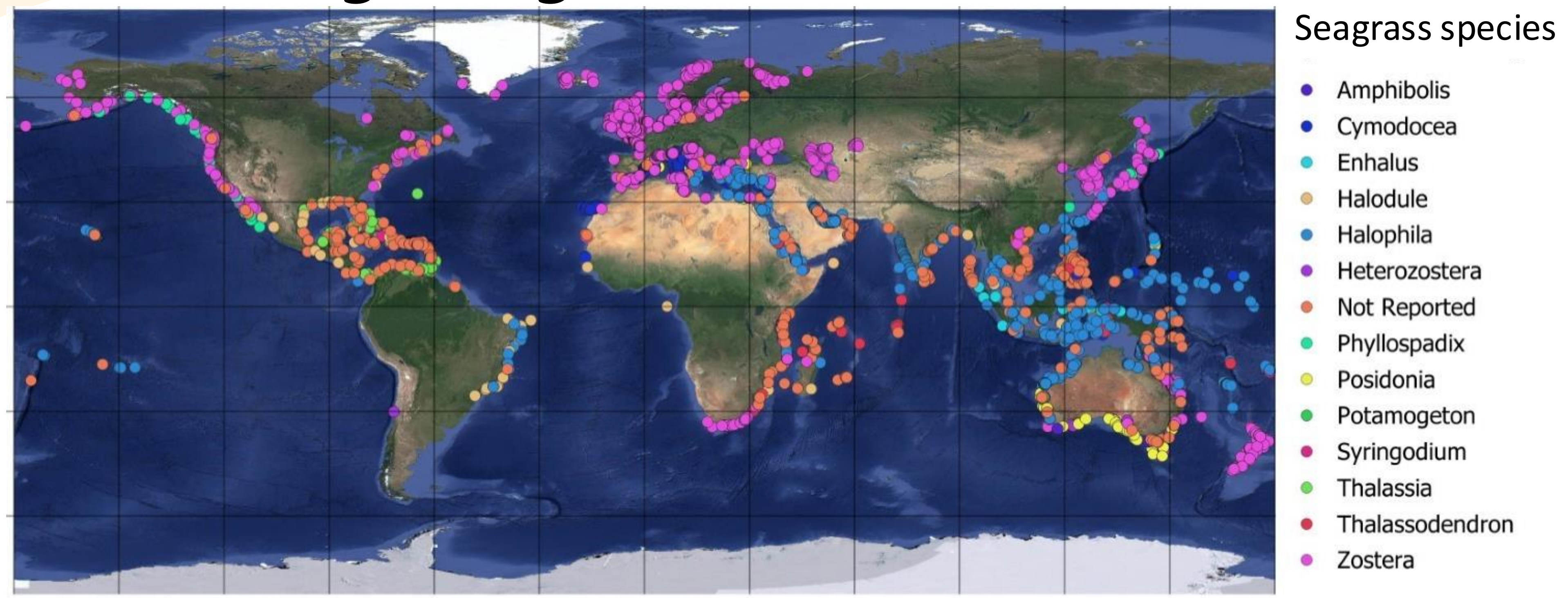

Mangroves restoration


Seagrass restoration


Oyster/Coral reef restoration
https://commons.wikimedia.org/w/index.php?curid=17781122

Seagrass role as NBS

Seagrass global distribution



- **Seagrass** are a group of marine Angiosperm that adapted to life within the coastal zone.
- They provide **critical ecosystem services** that support both the environment and the human well being.
- Globally, seagrass meadows are experiencing a **decline** due to climate change and human-induced stressors.

Ecosystem Services of seagrass

1. **Coastal protection:** sediment stabilization, **removal of wave and flow energy.**
2. **Carbon Sequestration:** captures and store carbon dioxide (blue carbon).
3. **Biodiversity and habitat support:** provides nursery ground for fish and invertebrates.
4. **Water quality improvement:** enhance water clarity and filters pollutants and excess nutrients.

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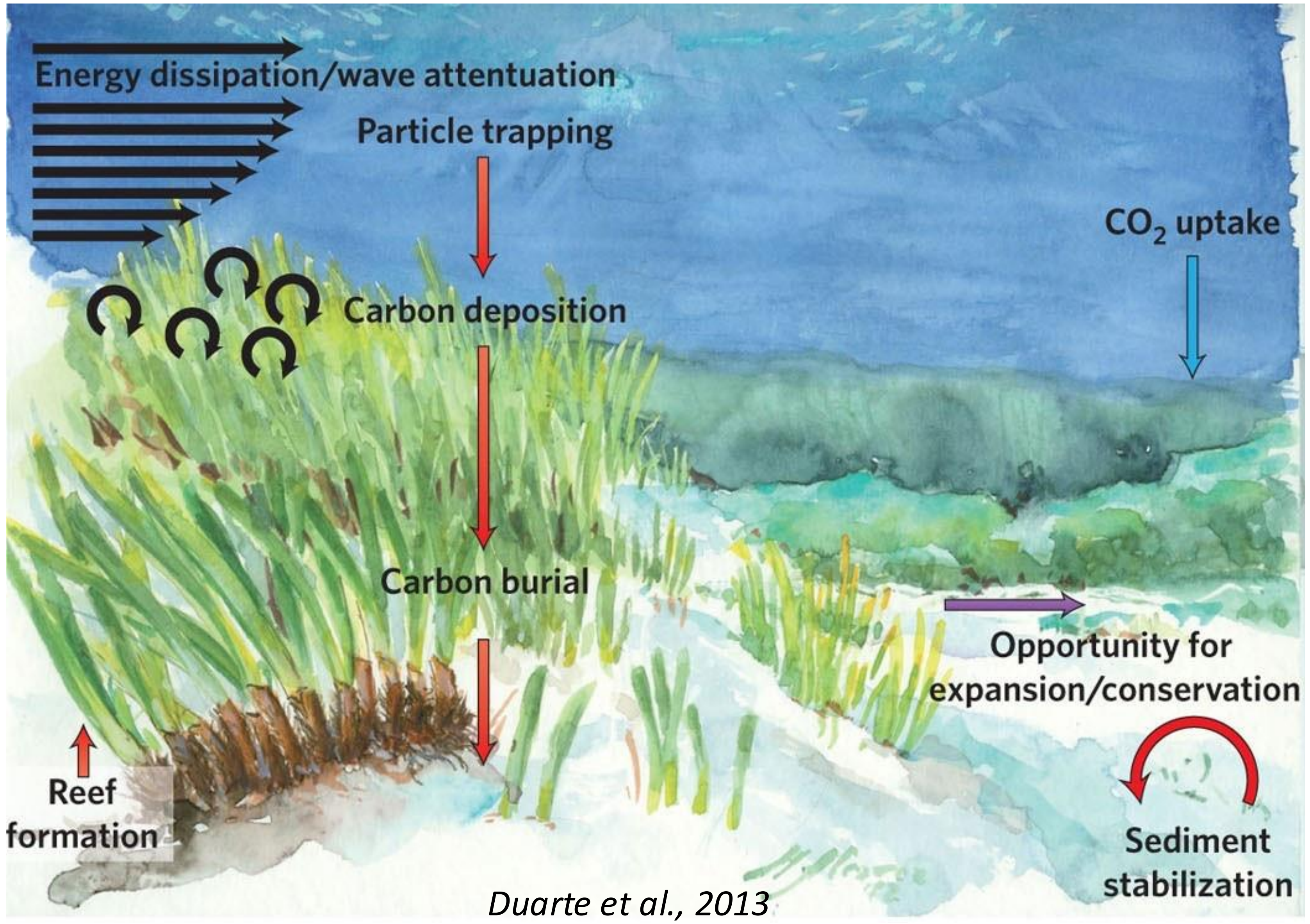
How can we assess coastal hazard reduction provided by seagrass?



Duarte et al., 2013

3. Digital Twins of the Ocean (DTO)

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What is a Digital Twin of the Ocean?

The basic concept

A digital twin is a virtual replica of a real-world object, system, or process that allow simulation, analysis and prediction of the system's behaviour and performance, combining ocean observations, artificial intelligence and advance modelling.

The concept can be applied to the studying of the ocean

- Computational oceanography has come of age (Haine et al., 2021) and **ocean models can reproduce realistic structures** in the ocean so that they can be used for Digital Twin experiments.
- DTOs can be used to propose the best design of solutions to problems such as **Coastal hazard reduction** (Pillai et al. 2022).

The assessment of seagrass as NBS for coastal hazard reduction can be carried out with a suite of modelling tools that realize the DTO.

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Ocean model

SHYFEM-MPI

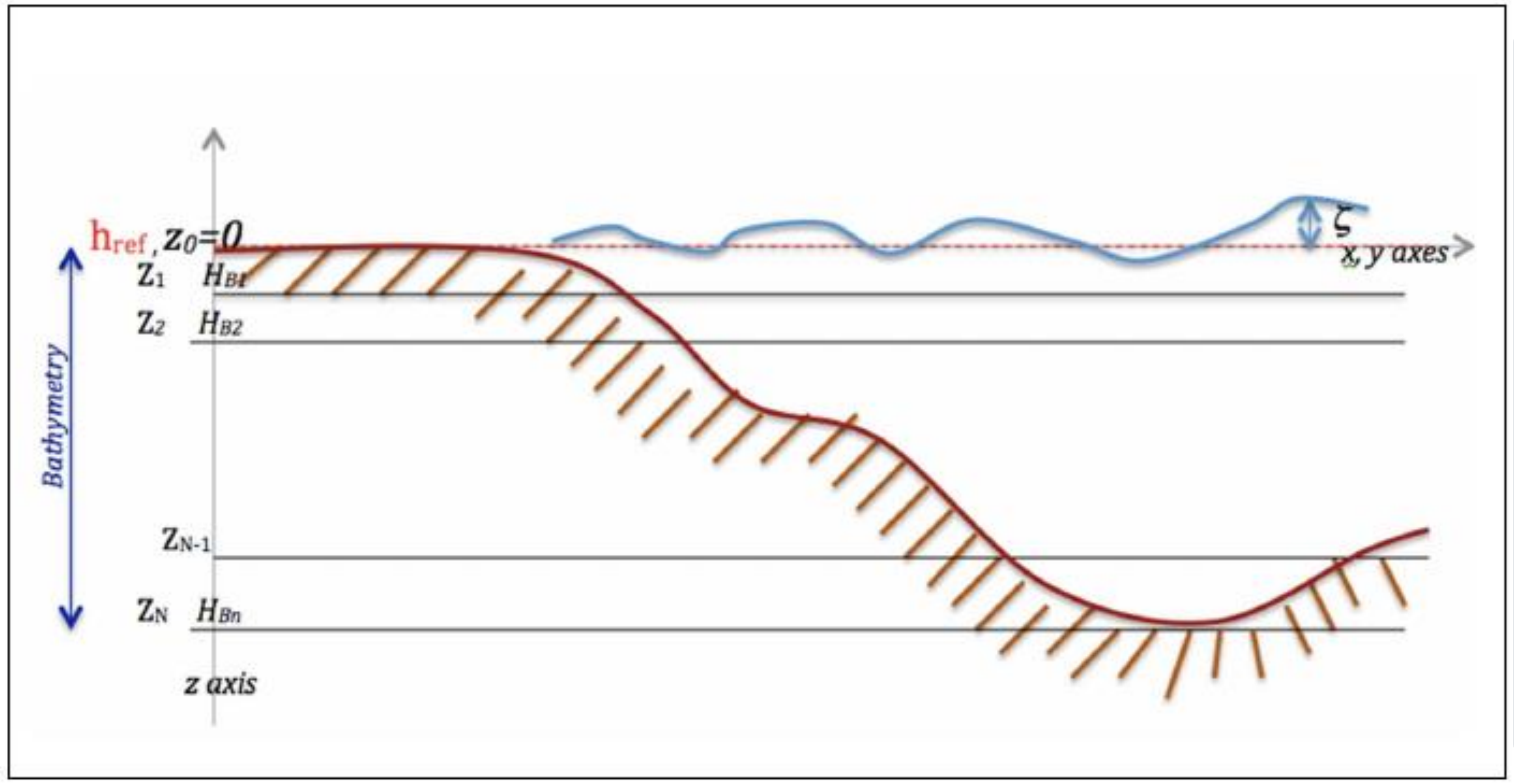
Wave model

WaveWatch III ®

Ocean Circulation Model

- **SHYFEM-MPI** (System of HYdrodynamic Finite Element Modules MPI; Micaletto er al., 2021) is a three-dimensional finite element model, that solves the primitive equations for the ocean under hydrostatic and Boussinesq approximation.
- **Unstructured grid** approach on Arakawa B-type grid triangular mesh.
- **semi-implicit** time scheme.
- **Vertical mixing: k-epsilon** turbulence model (from GOTM model; Burchard et al. 1999).
- **Horizontal viscosity: Smagorinsky formulation.**
- **Air-sea interaction: MFS bulk formulae** to parametrize the meteorological forcing.

Maicut et al., 2021



- **Operational activities:** AdriFS system (https://adri.cmcc.it/).
- **Nature Based Solutions:** Seagrass module integrated in the model.
- **Sediment transport:** Coupling with sediment transport model SEDTRANS.
- **Waves:** Coupling with wind wave model WAVEWATCH III (ongoing).

Wave Model

- **WAVEWATCHIII (WW3)** is community **third-generation wave model** (Tolman et al., 2019) and solves the random phase spectral action density balance equation for wavenumber-direction spectra, including options for **shallow-water (surf zone) applications**.
- **Unstructured-grid** component (Mentaschi et al., 2019; Pillai et al., 2022).

Governing equation

$$\frac{\partial N}{\partial t} + \nabla \cdot \vec{c}N = \frac{S}{\sigma}$$

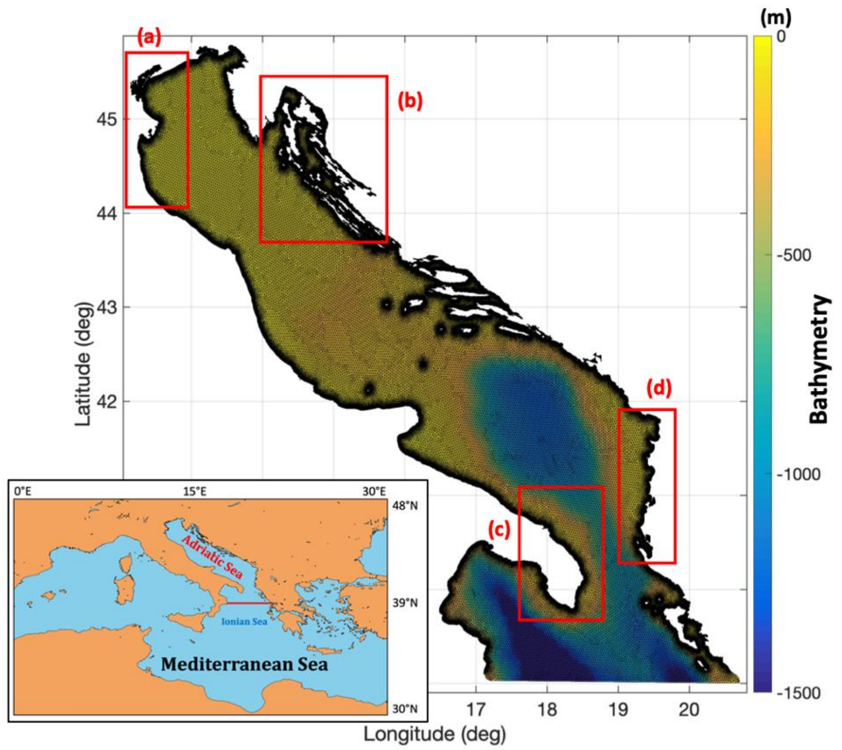
S = source terms,
σ = intrinsic frequency,
c = phase velocity

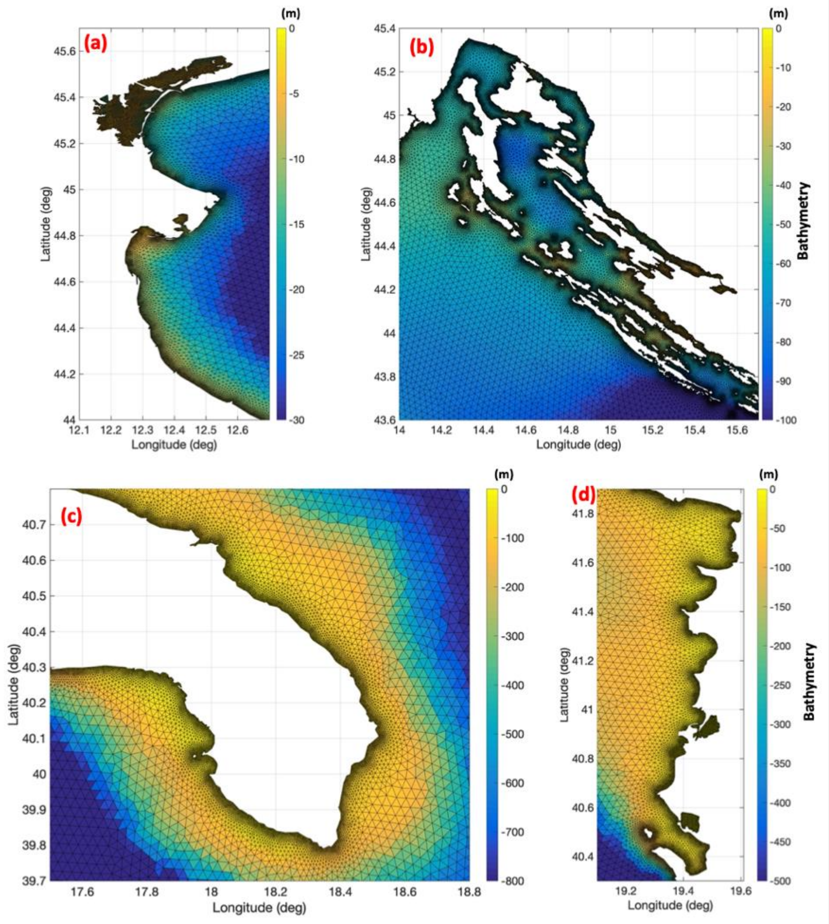
Spectral density of wave action

$$N = N(k, \theta, \vec{x}, t)$$

χ= nodes= 10^6
κ= frequencies
ϑ= directions

ADRIFS





- **Operational activities:** AdriFS system (https://adri.cmcc.it/).
- **Nature Based Solutions:** Seagrass module integrated in the model.
- **Coupling with currents:** Application to study Medicane effects at coast (Causio et al. 2025).
- **Global application:** Global unstructured grid to study the effects of hurricanes (**Uglobw**).

Seagrass Parameterization

Ocean model

SHYFEM-MPI

Wave model

WaveWatch III ®

Seagrass drag equation

$$F_{veg,x} = \frac{1}{2} C_{Dv} D_v N_v |\vec{u}| u$$

C_{Dv}: drag coefficient
D_v : Seagrass stem diameter
N_v: Seagrass density (stems/m^2)

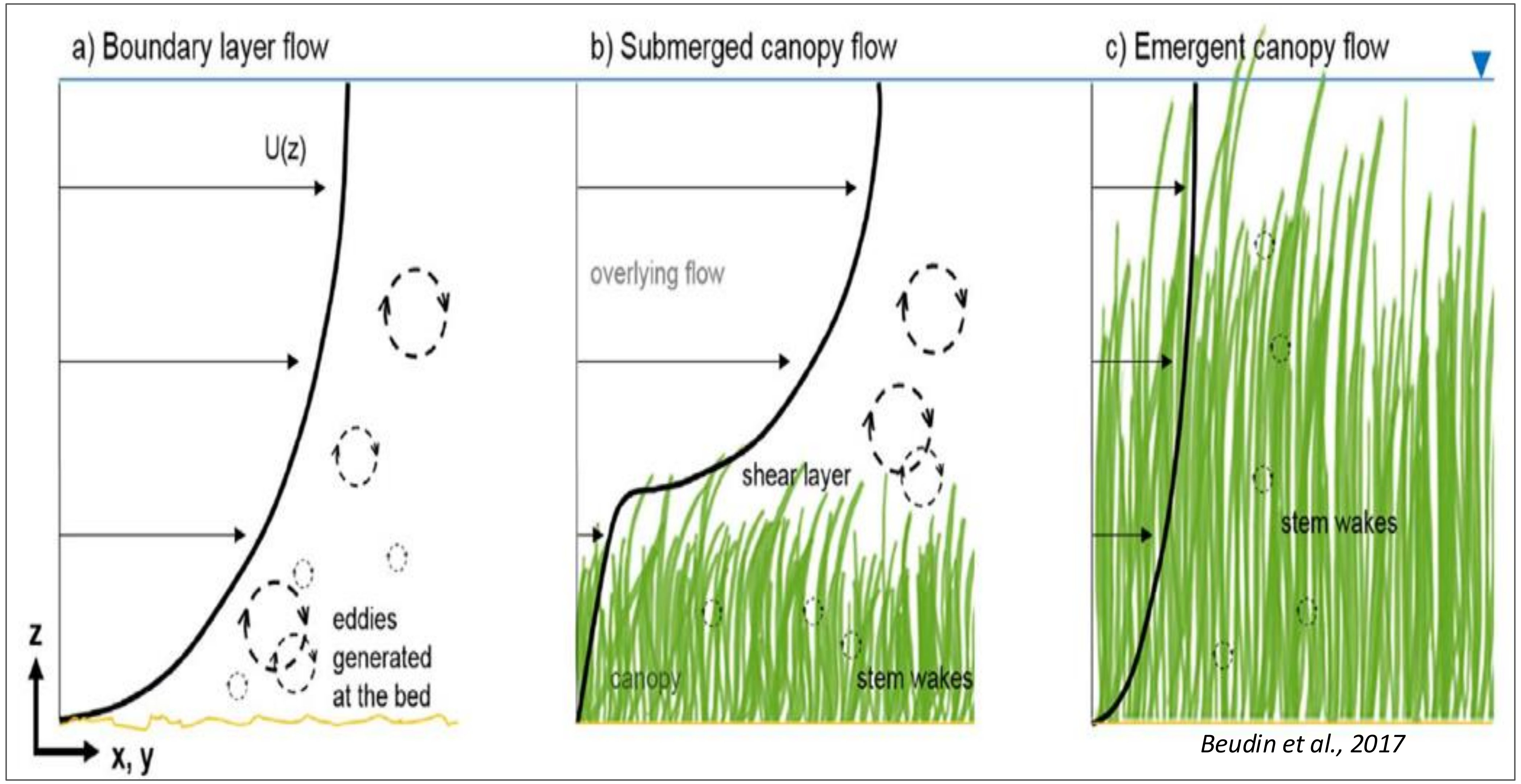
Seagrass turbulence terms

$$\frac{\partial k}{\partial t} + \vec{U} \cdot \nabla k = \frac{\partial}{\partial z}\left(\frac{A_v}{\sigma_k}\frac{\partial k}{\partial z}\right) + P_s + \boxed{P_d} + B - \epsilon$$

$$\frac{\partial \epsilon}{\partial t} + \vec{U} \cdot \nabla \epsilon = \frac{\partial}{\partial z}\left(\frac{A_v}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial z}\right) + \frac{\epsilon}{k}\left(c_{\epsilon 1} P_s + \boxed{c_{\epsilon 4} P_d} + c_{\epsilon 3} B - c_{\epsilon 2}\epsilon\right)$$

$$P_d = \frac{1}{2} C_D b_v N_v |\vec{u}|^3$$

Renneau et al., 2012



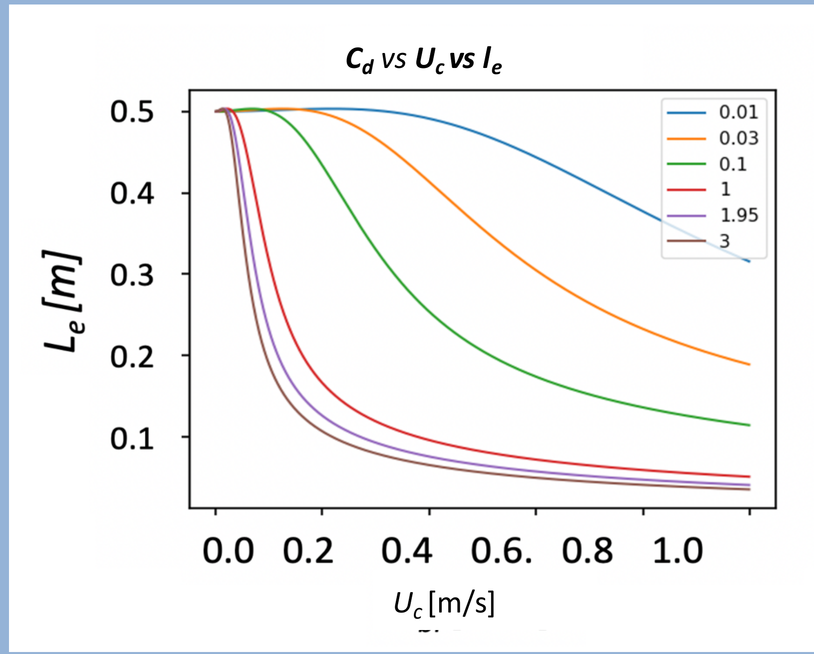
Beudin et al., 2017

Seagrass flexibility

$$l_e = l_v - \frac{\left(1 - 0.9 Ca^{-1/3}\right)}{1 + Ca^{-3/2}\left(8 + B^{3/2}\right)} l_v$$

$$B = \frac{(\rho - \rho_v) g b_v t_v l_v{}^3}{EI}$$

$$Ca = 0.5 \frac{\rho C_D b_v U^2 l_v{}^3}{EI}$$



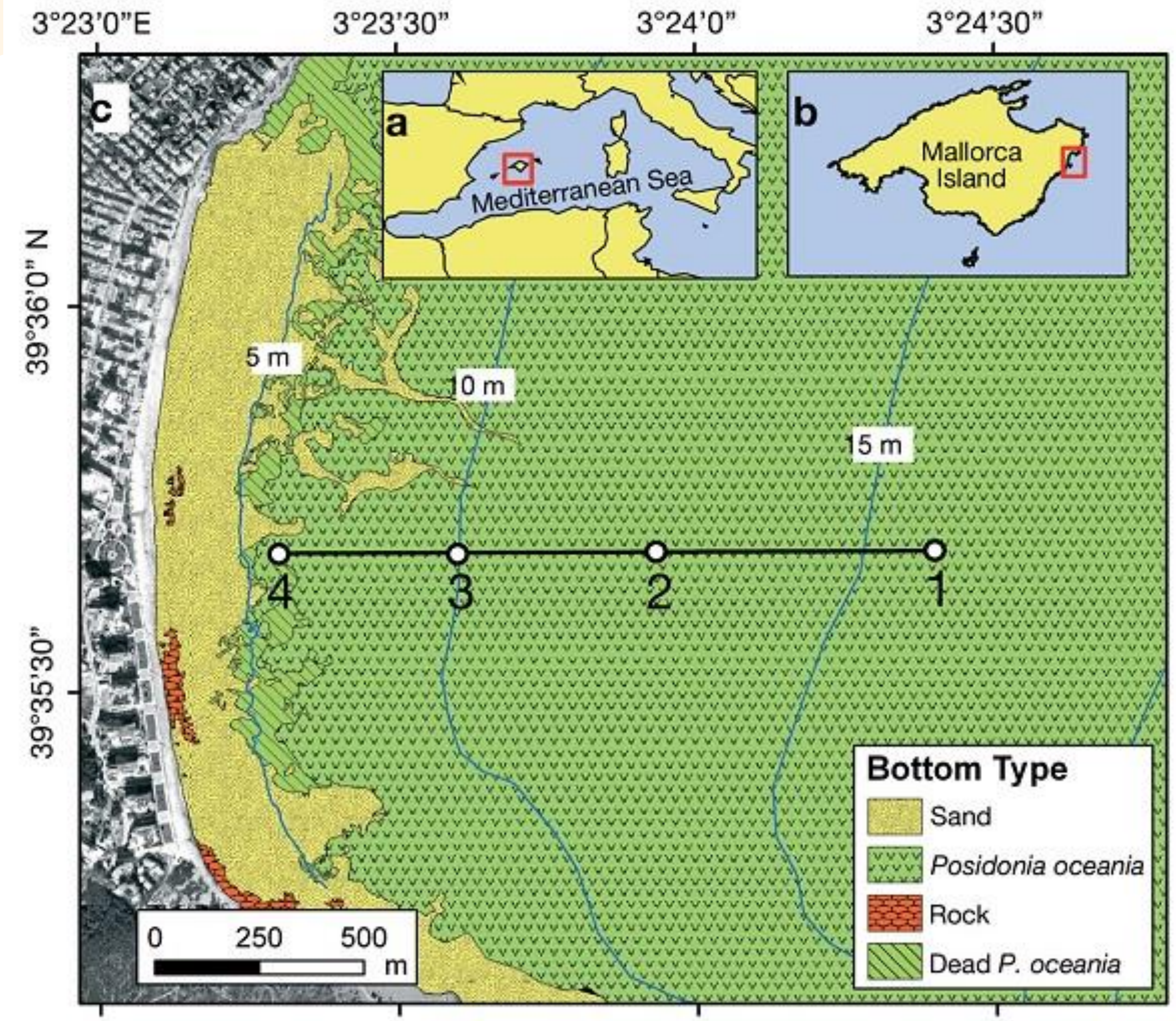
Instead using the vegetation length at rest l_v , we use an effective length l_e affected by the near-bottom water velocity (U_c)

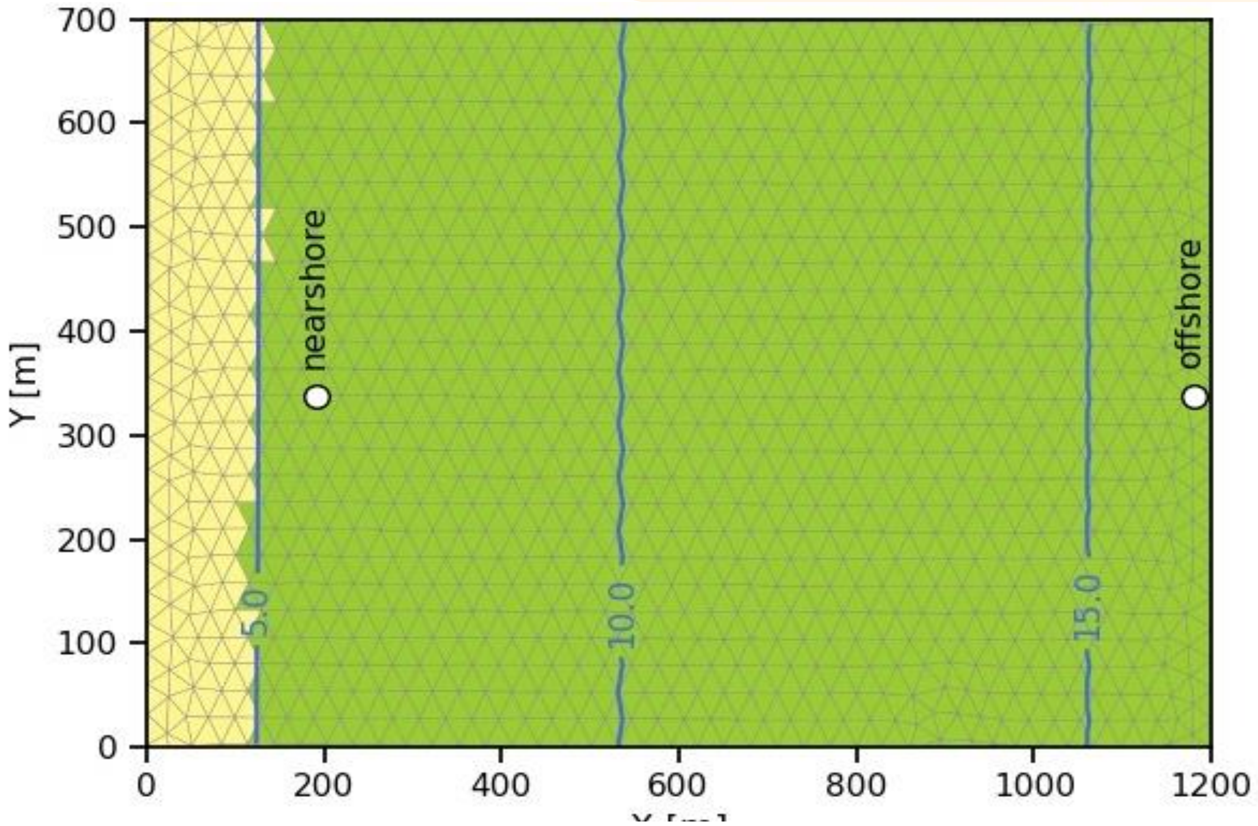
Luhar and Nepf (2011)

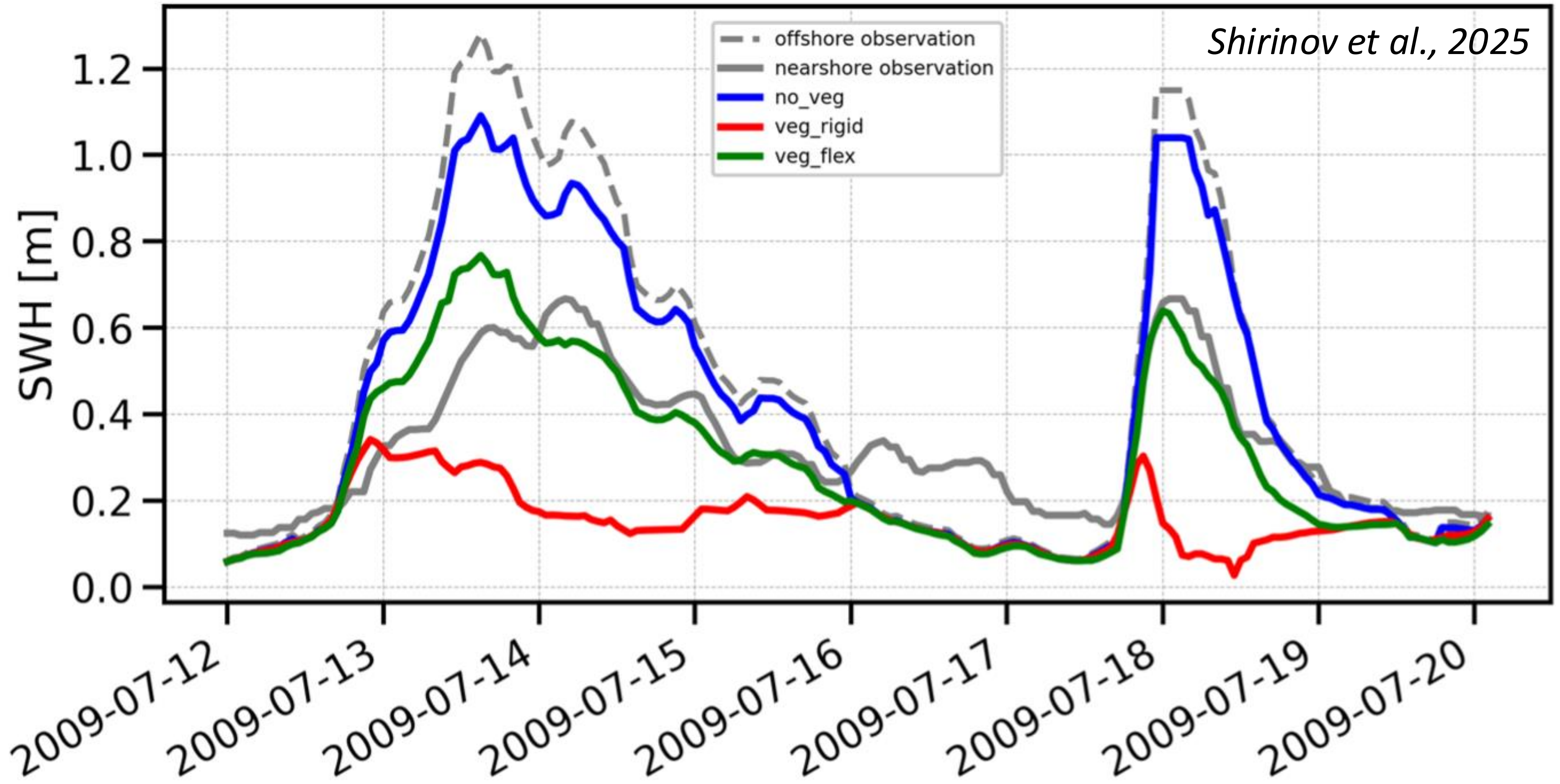
Flow-dependent effective length l_e

Seagrass Parameterization

Study area (Cala Millor, Mallorca, Spain)







- The flexibility of seagrass is tested reproducing the results of Infantes et al., 2012.
- The height of seagrass stem is replaced with an 'effective lenght' that account for seagrass flexibility.
- Overestimation of wave damping with rigid seagrass.

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4. Applications of DTO to NBS Assessment

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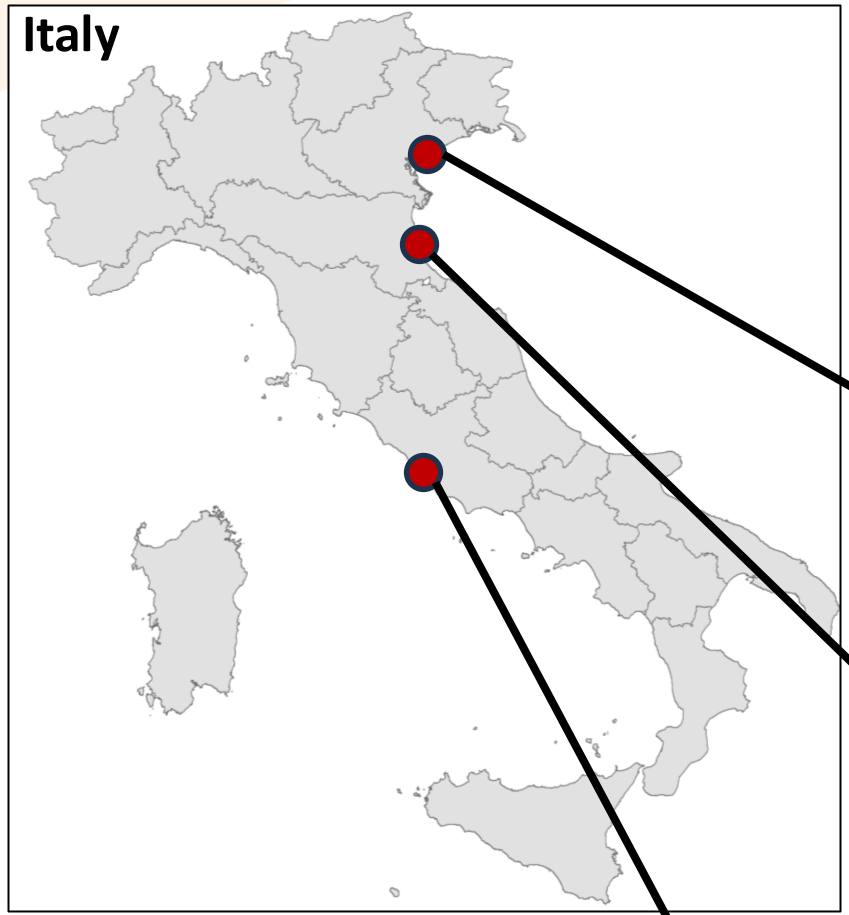
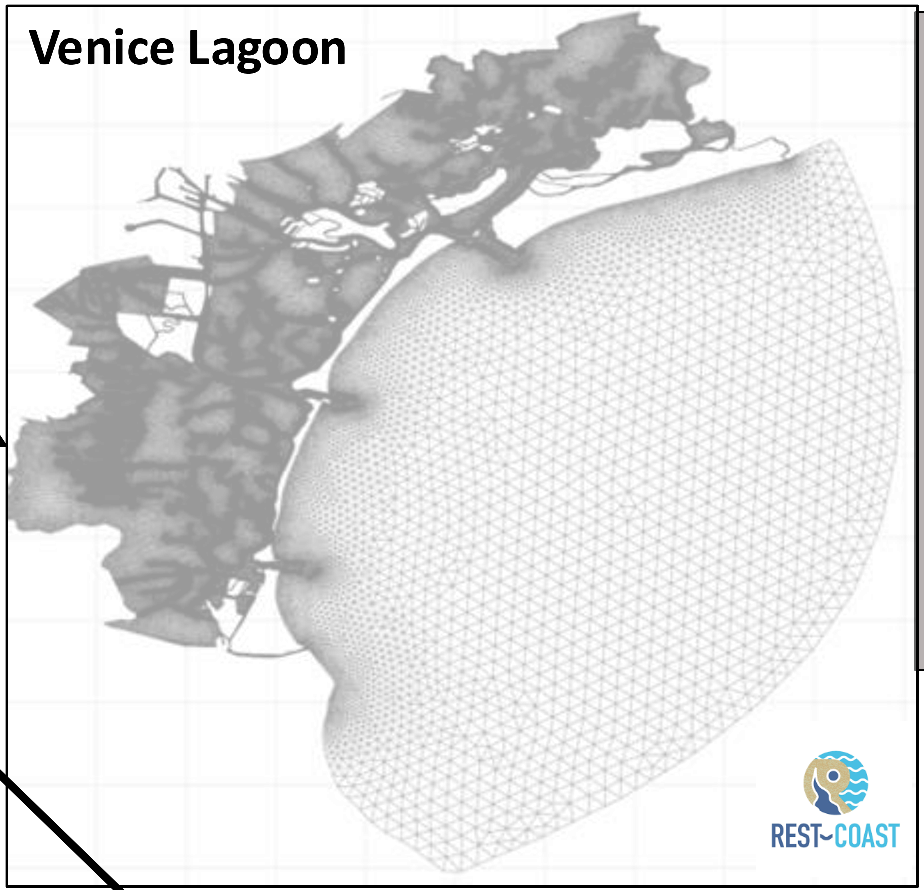
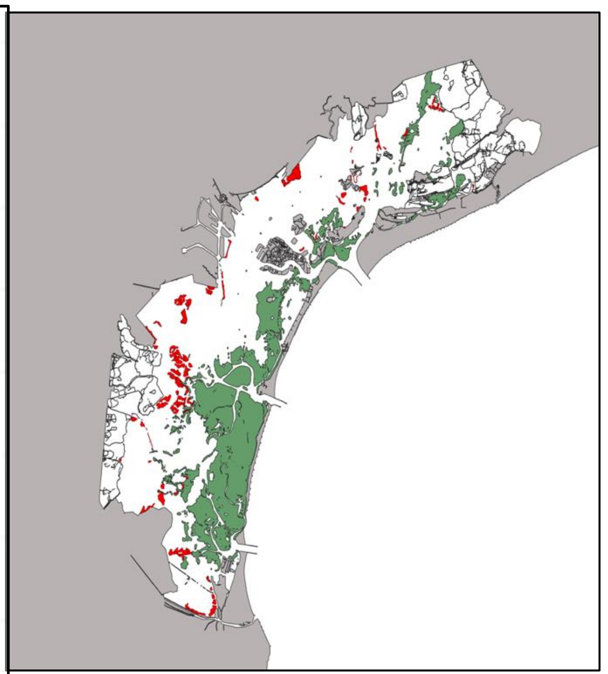
Study areas



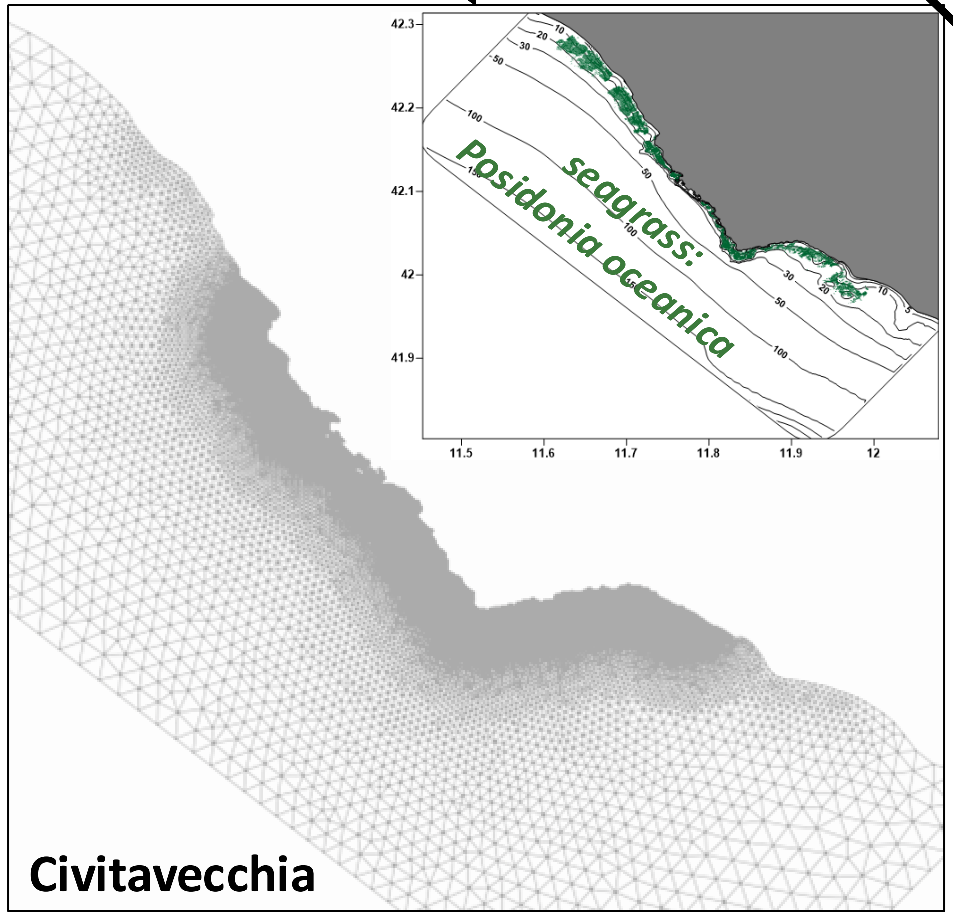


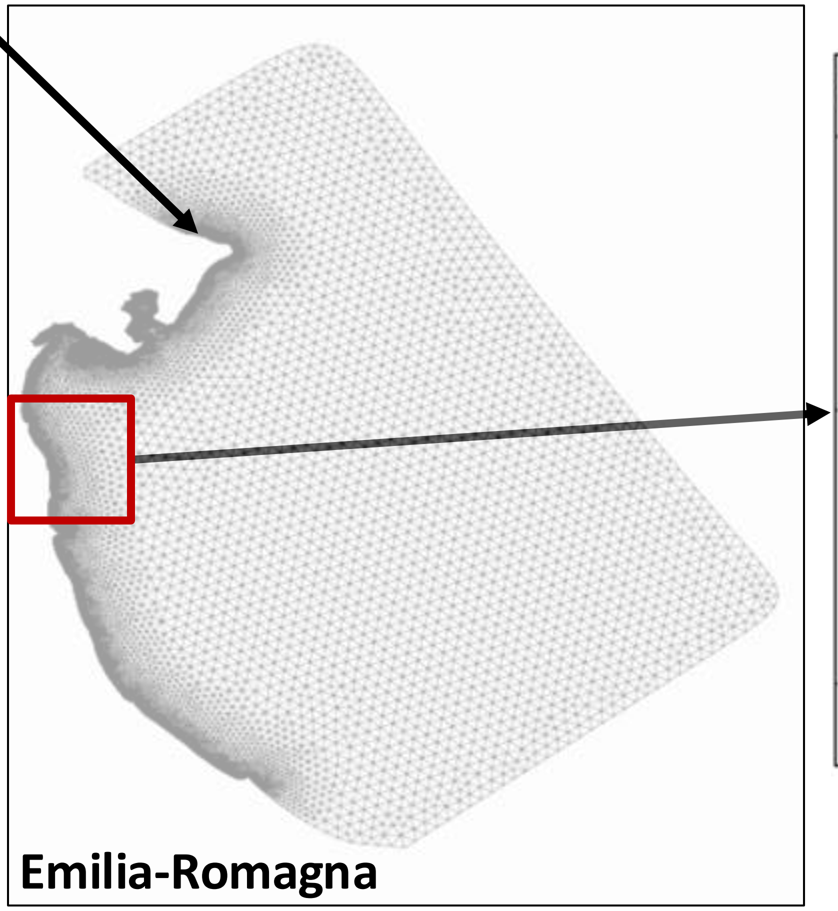


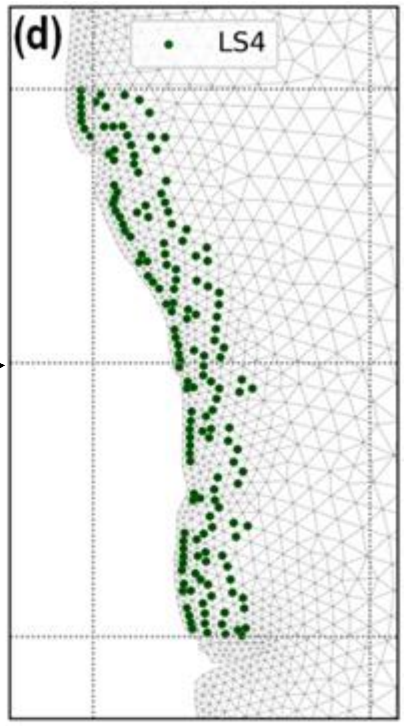
Seagrass: Zostera marina

Three areas are chosen as testcases around the Italian peninsula:

1) **Venice Lagoon**
2) **Civitavecchia**
3) **Emilia-Romagna**







Seagrass: Zostera marina

Posidonia o.

Zostera m.

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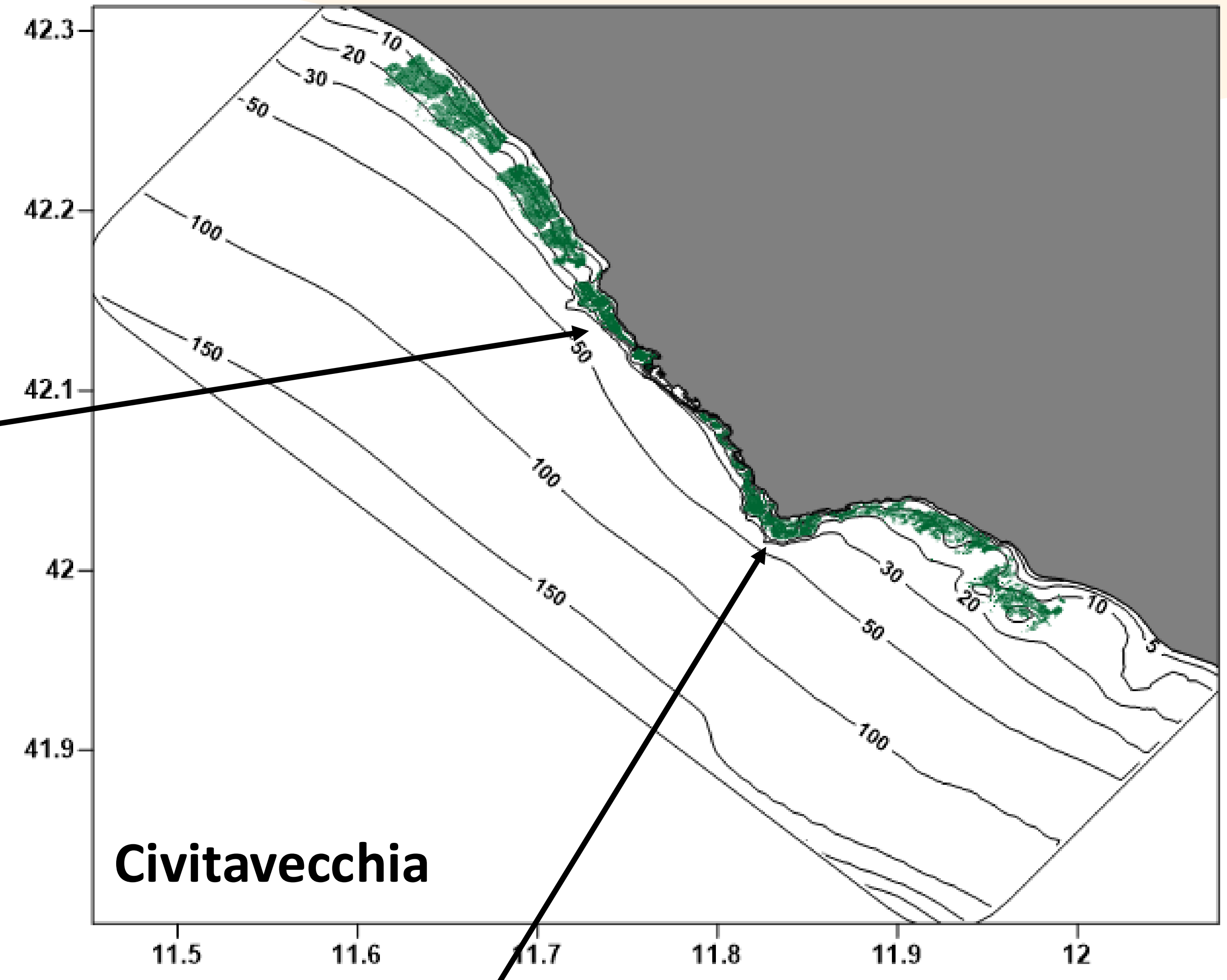
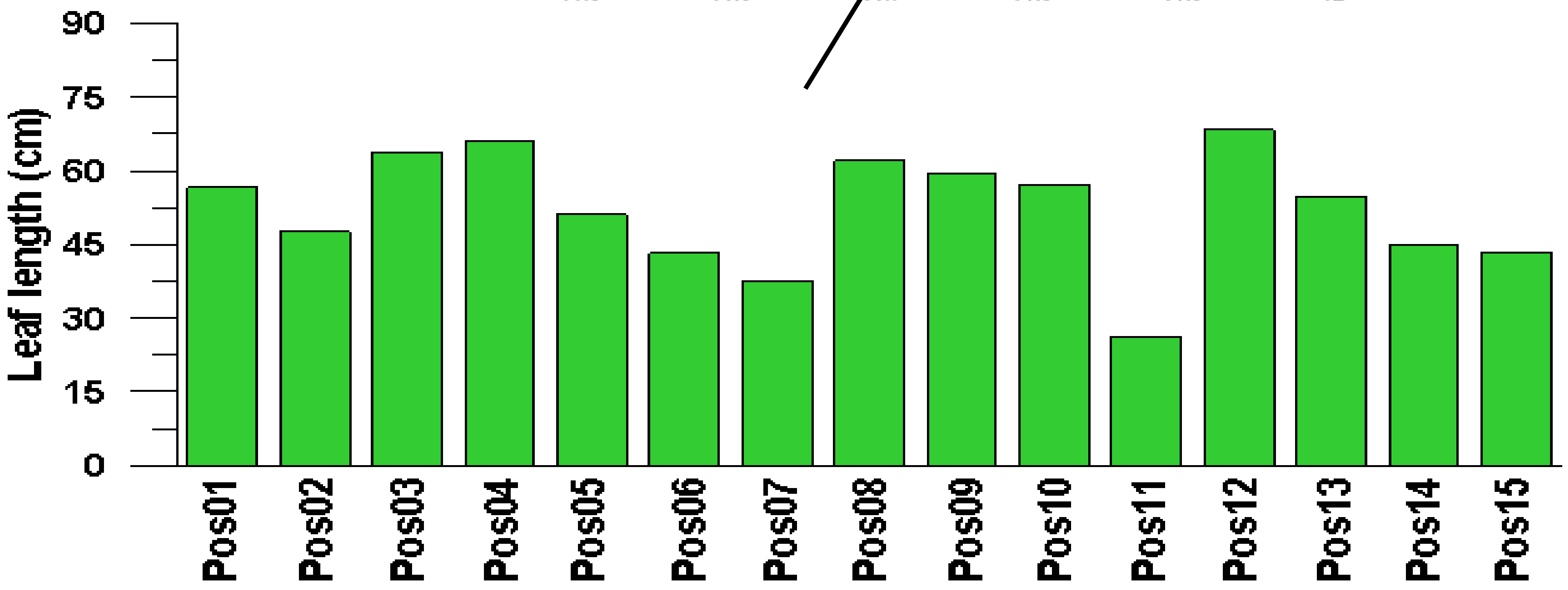
Seagrass Observations





Where available, data of **seagrass distribution** and observations of **seagrass physical feature** where integrated into the numerical models.

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Simulations Set-up

Ocean model

SHYFEM-MPI

- ***Meteorological Forcing:*** ECMWF IFS at 9km.
- ***Initial and open boundary conditions:*** CMEMS MFC analysis at 1/24 with tides.
- ***Bathymetry:*** Emodnet at 250 m
- ***Rivers:*** Observations (Po river) + climatology.

Wave model

WaveWatch III ®

- ***Meteorological Forcing:*** ECMWF IFS at 9km.
- ***Open boundary conditions:*** CMEMS waves dataset.
- ***Bathymetry:*** Emodnet at 250

Name of simulation	Seagrass
REF	No
SGRS	YES

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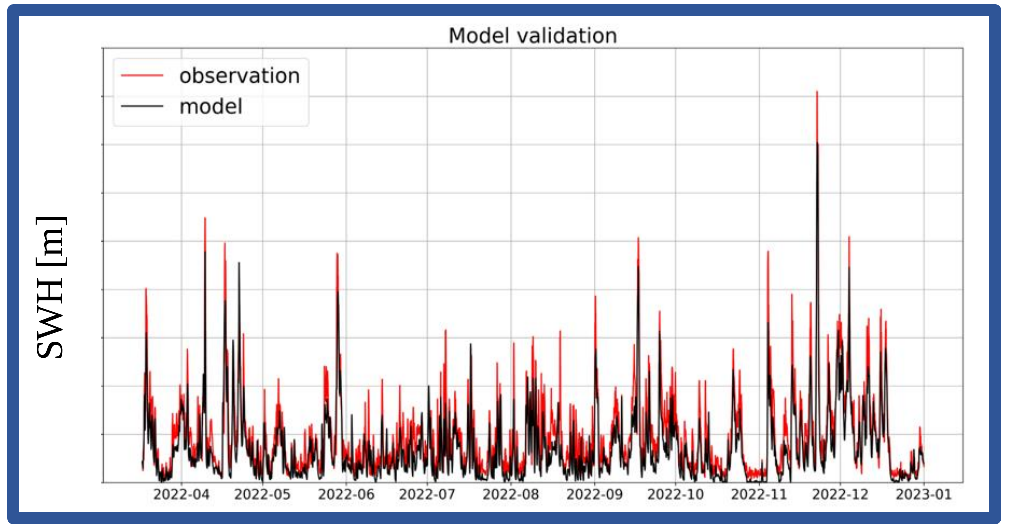
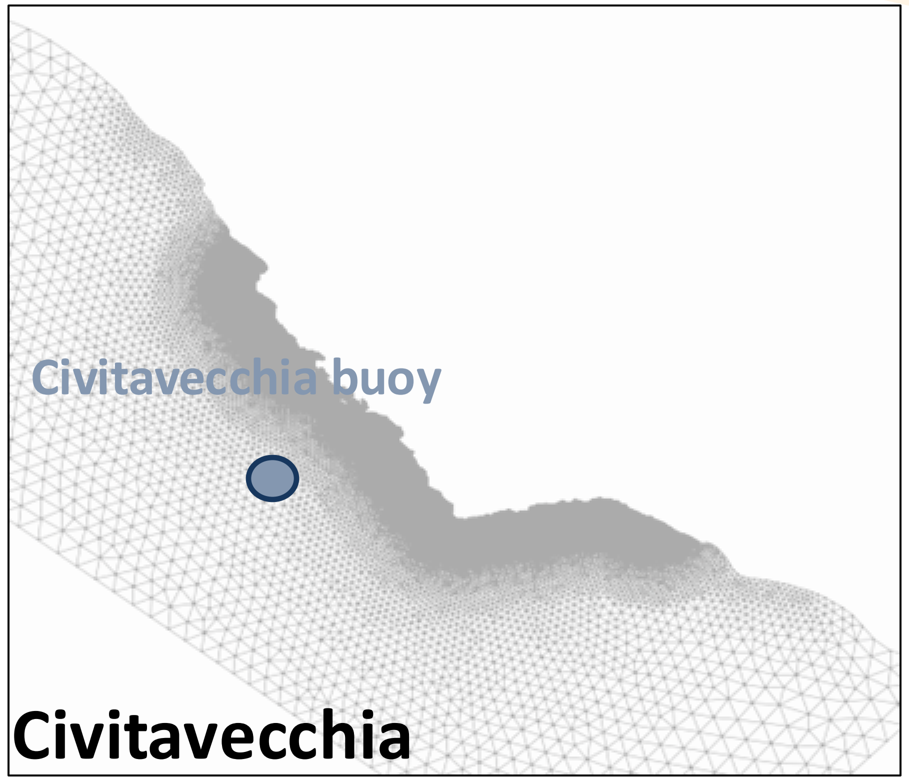
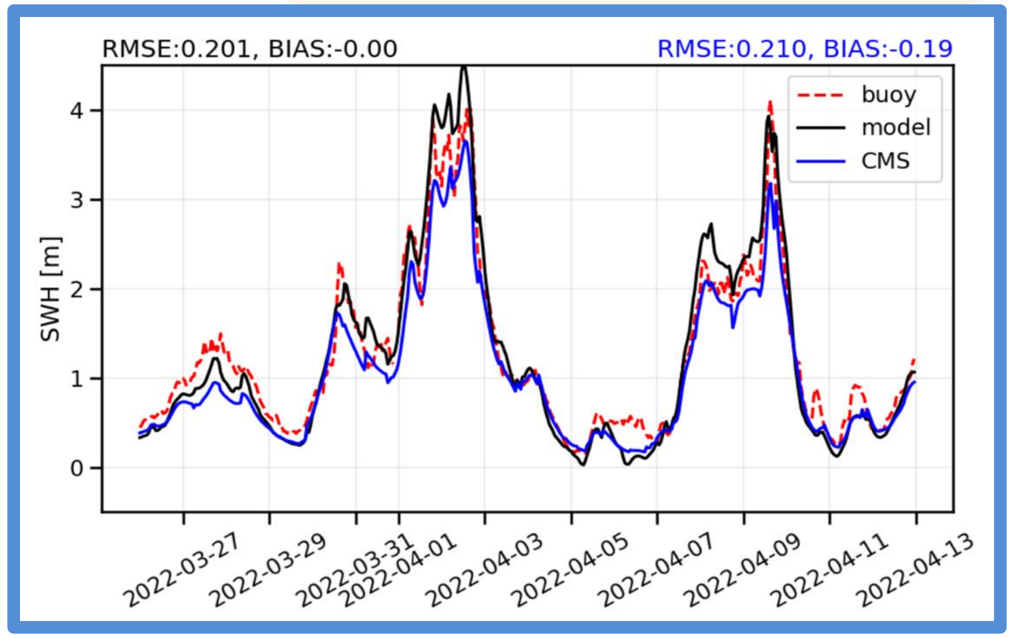
DTO Validation

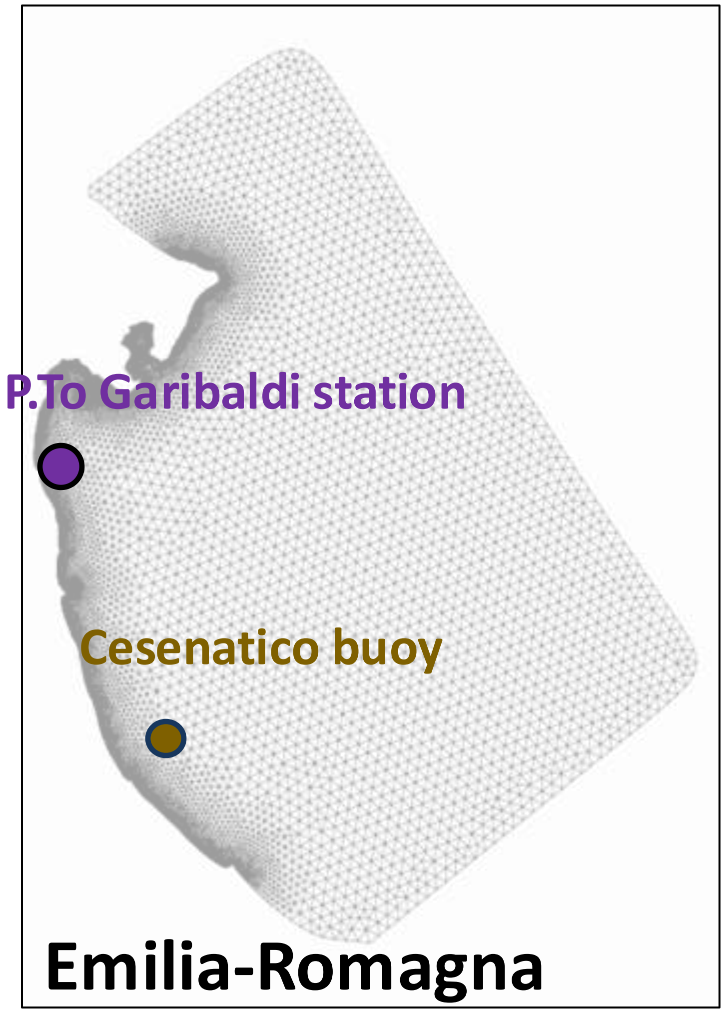
Acqua alta platform



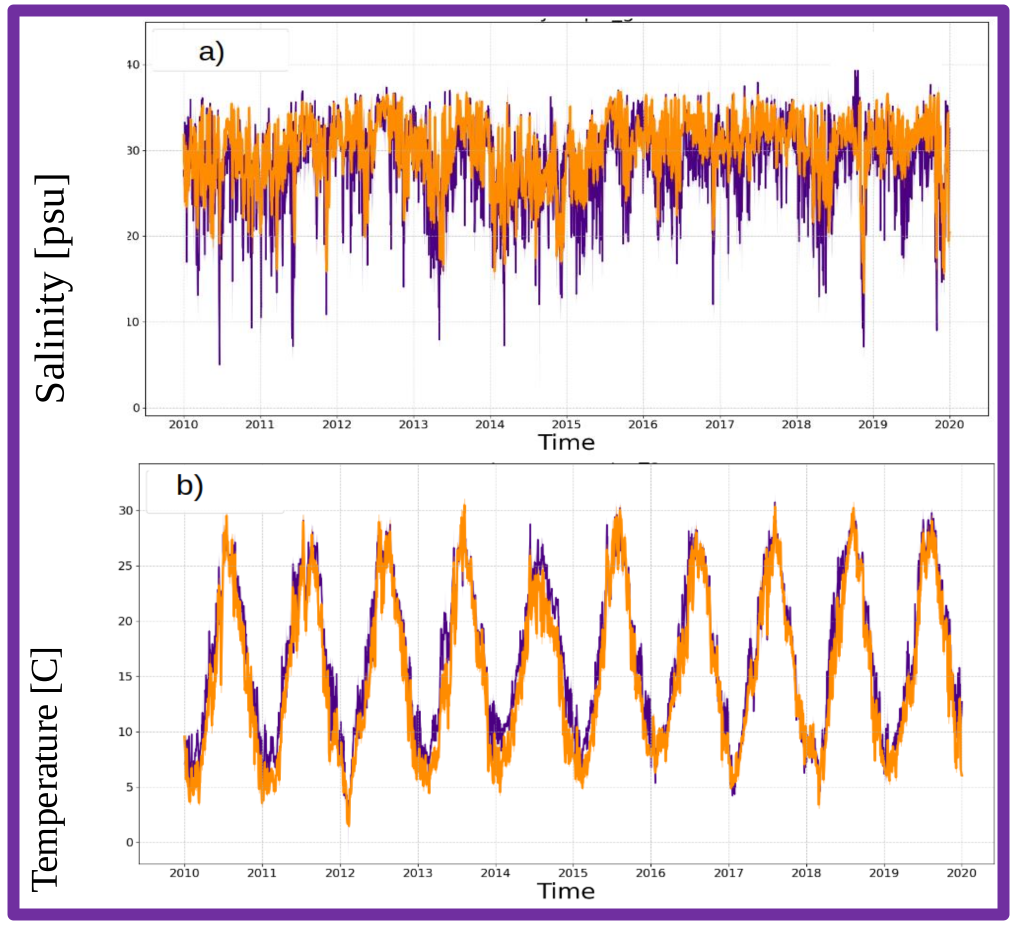


Civitavecchia buoy



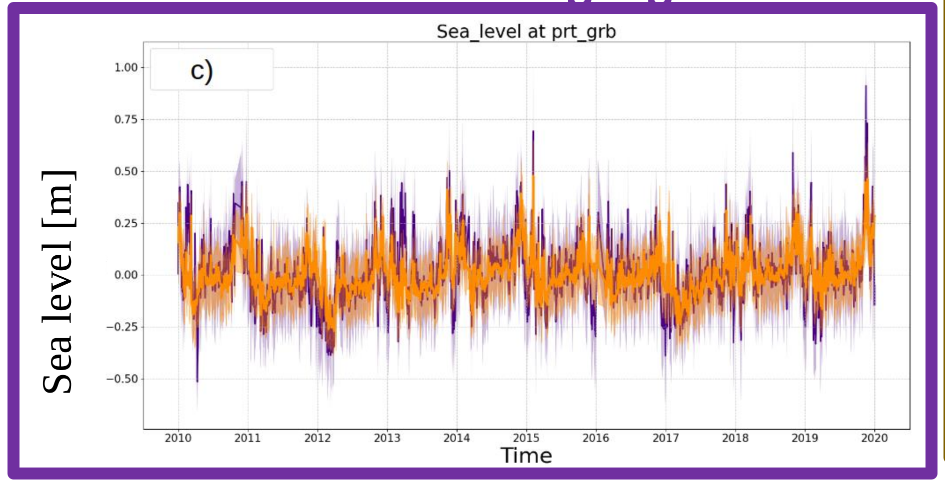


P.to Garibaldi station

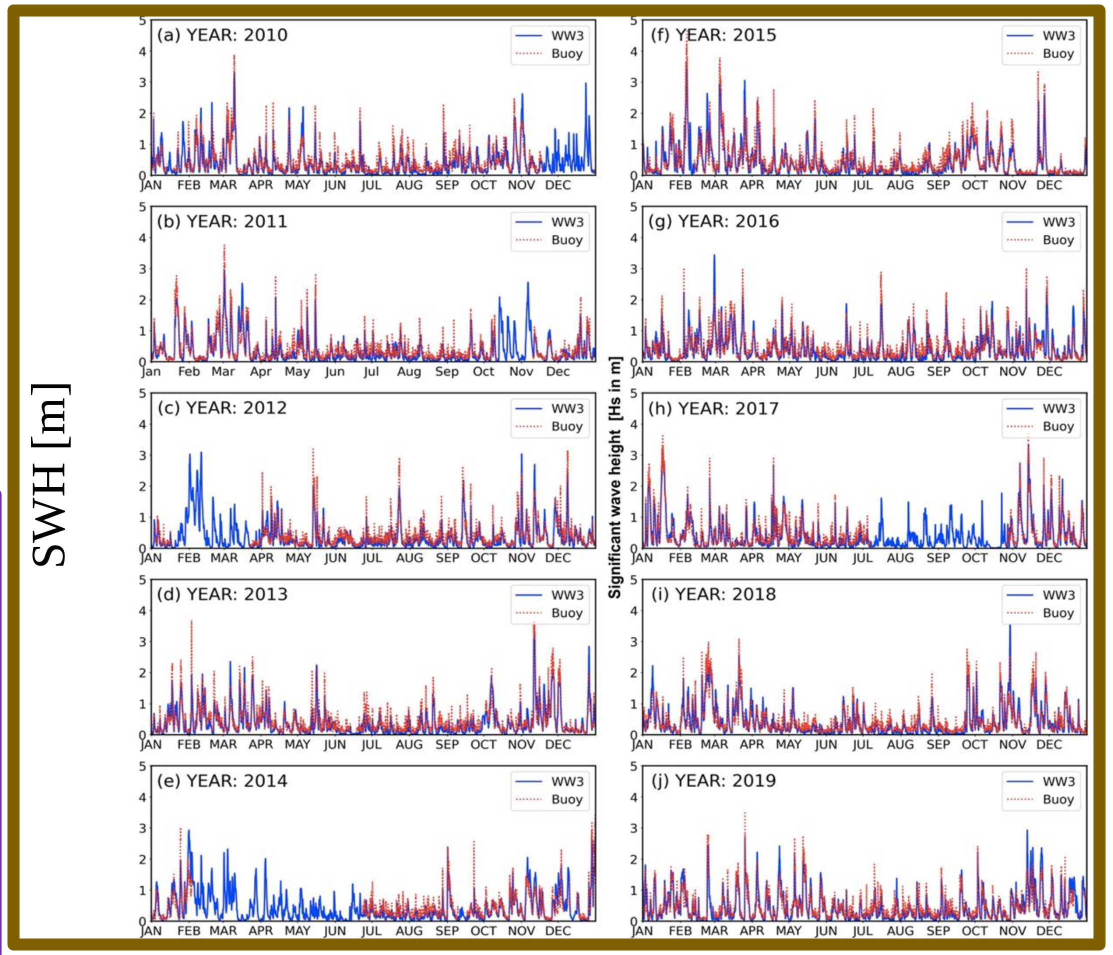


The models were validated with the available observations for **waves, temperature, salinity** and **sea level**.

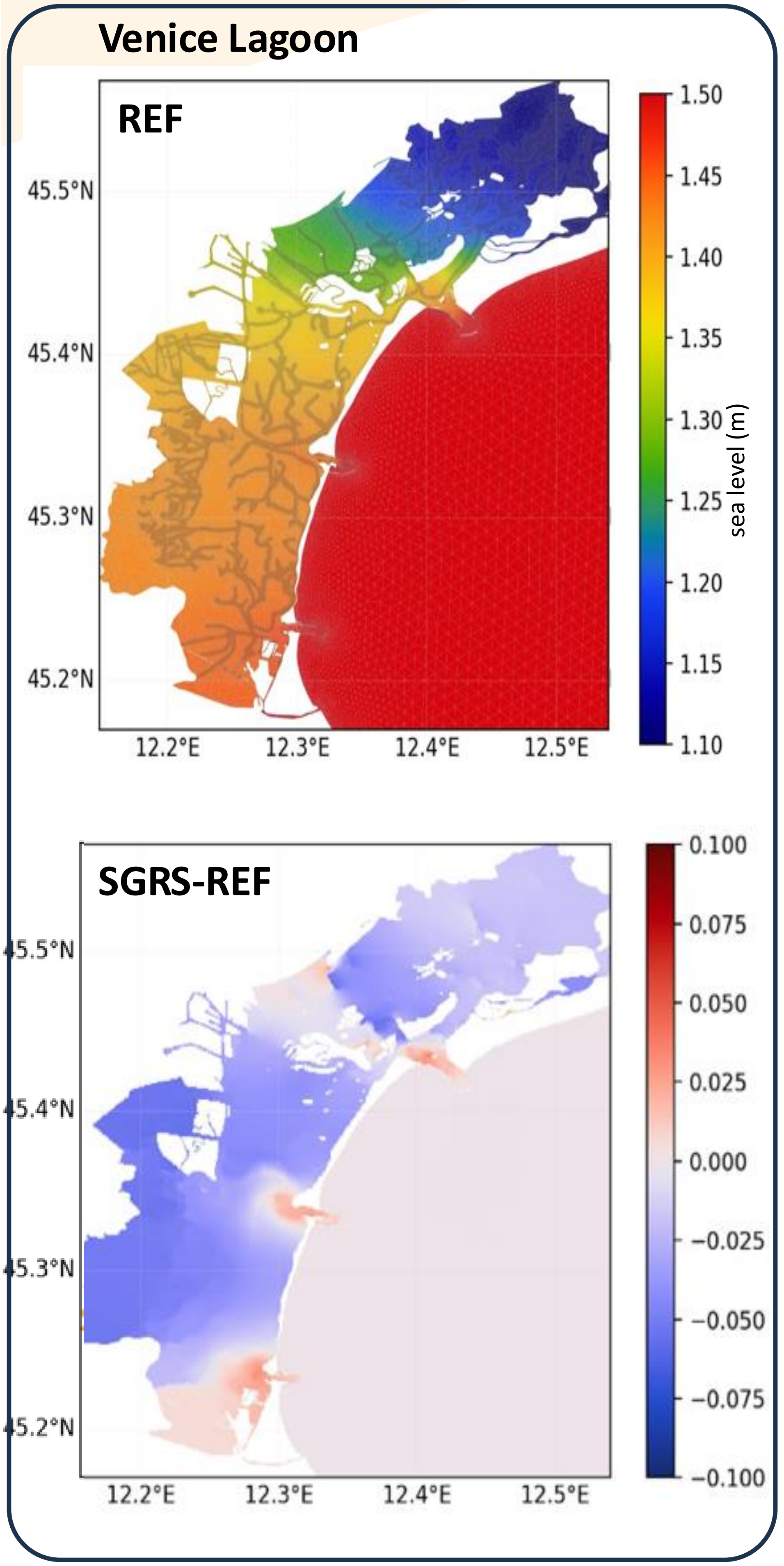
P.to Garibaldi tidegauge

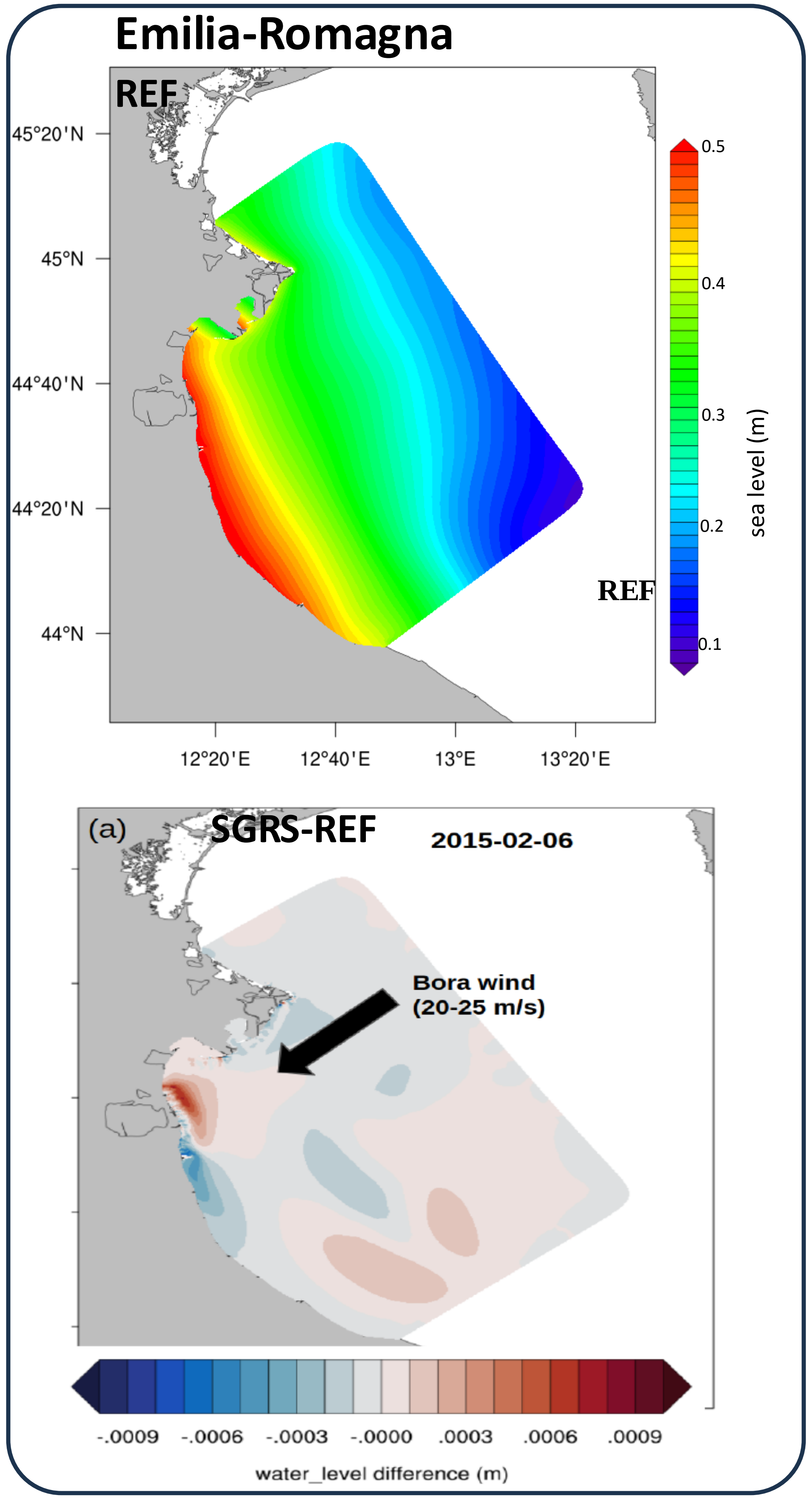


Cesenatico buoy



Sea Level



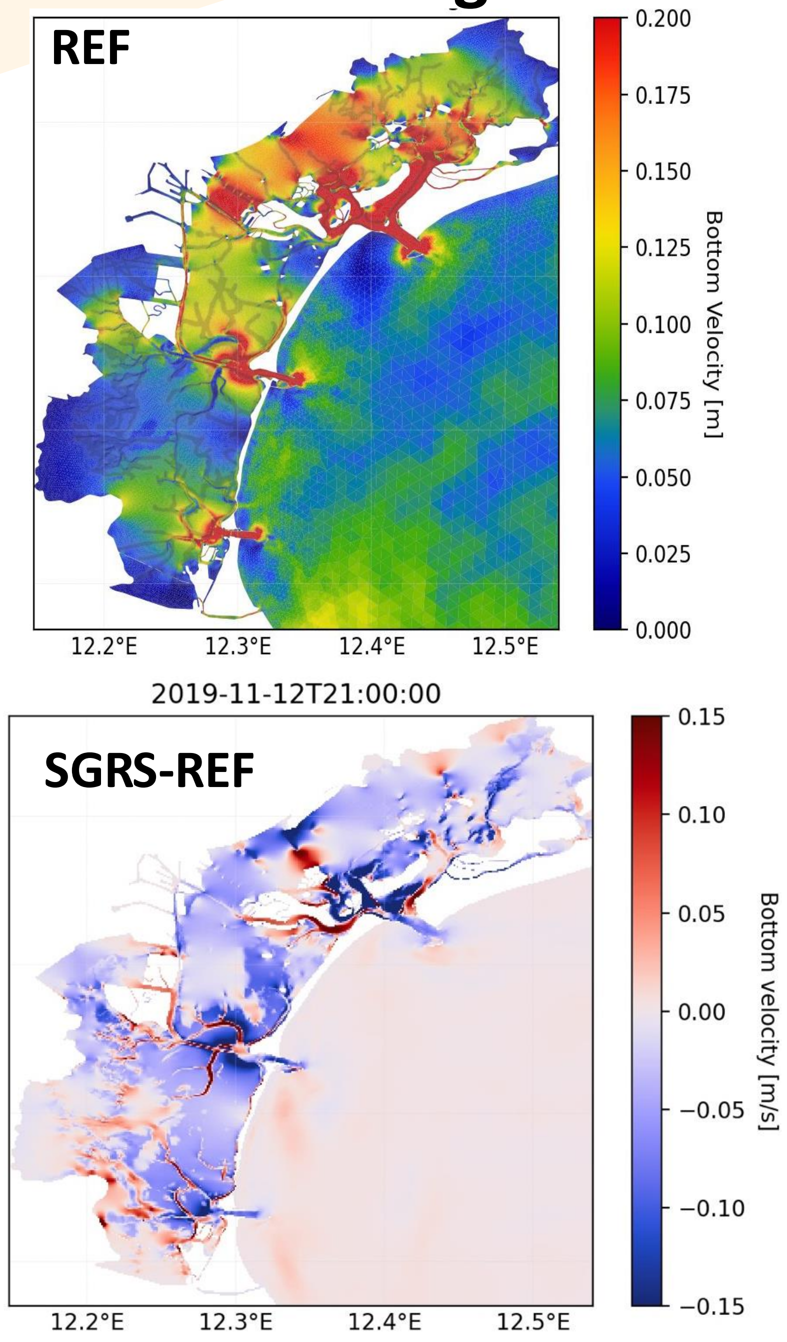


The effects of seagrass on the ocean and waves variables are evaluated with a What-if Scenario, comparing the **SGRS** simulation, where the **seagrass parameterization** is active, with the **REF** simulation with no seagrass. For each domain one or more **storm surge event** are considered in the simulations.

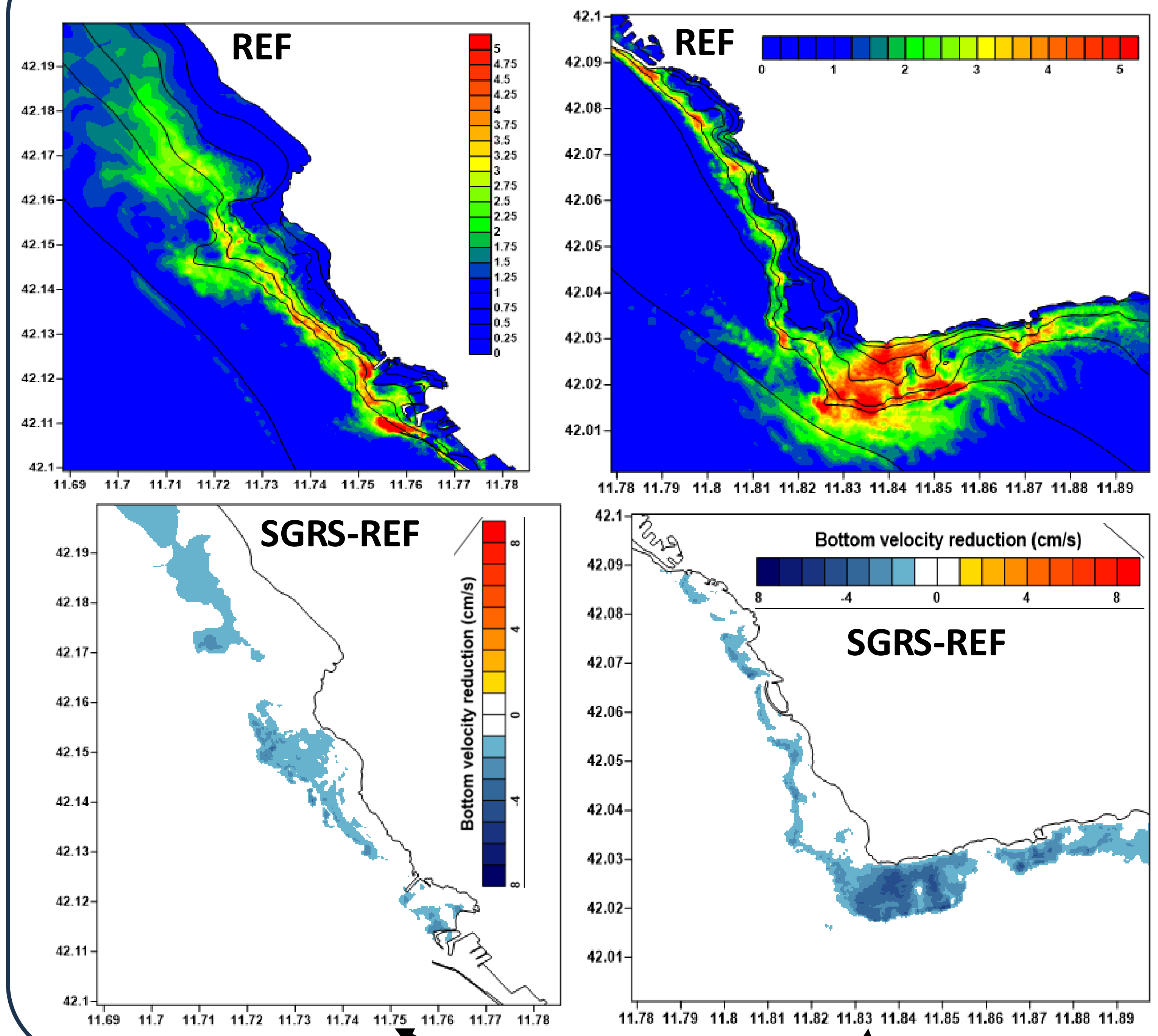
Sea level show an increase upstream the seagrass patch and a decrease downstream.
The effects are negligible in open coastal areas (*e.g.* **Emilia-Romagna coast**), however, in shallow closed areas like the **Venice Lagoon** the sea level reduction due to seagrass could reach **5-10%**.

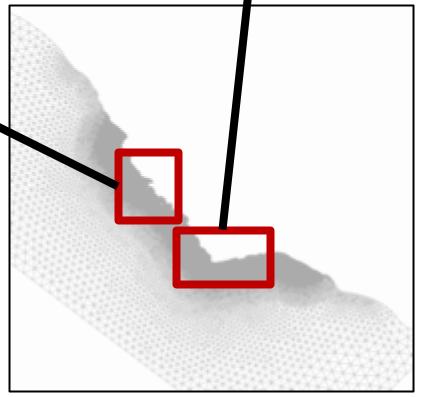
Currents velocity

Venice Lagoon

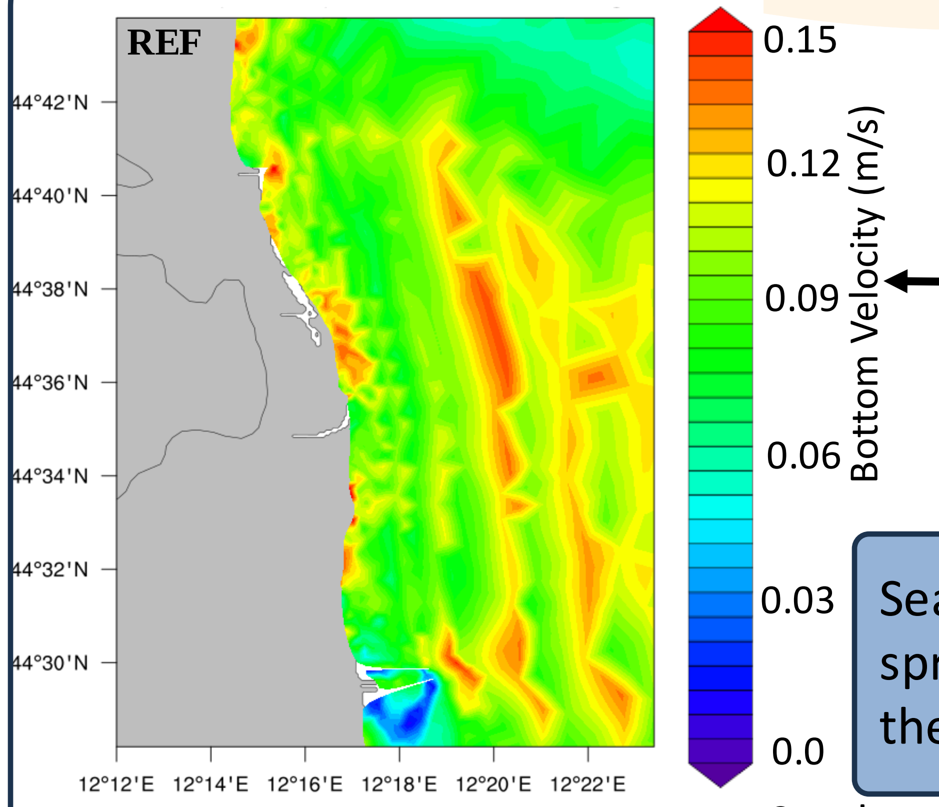


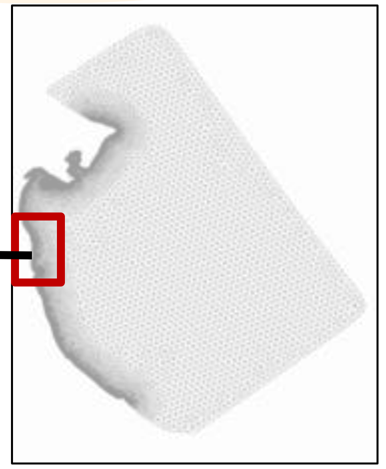
Civitavecchia



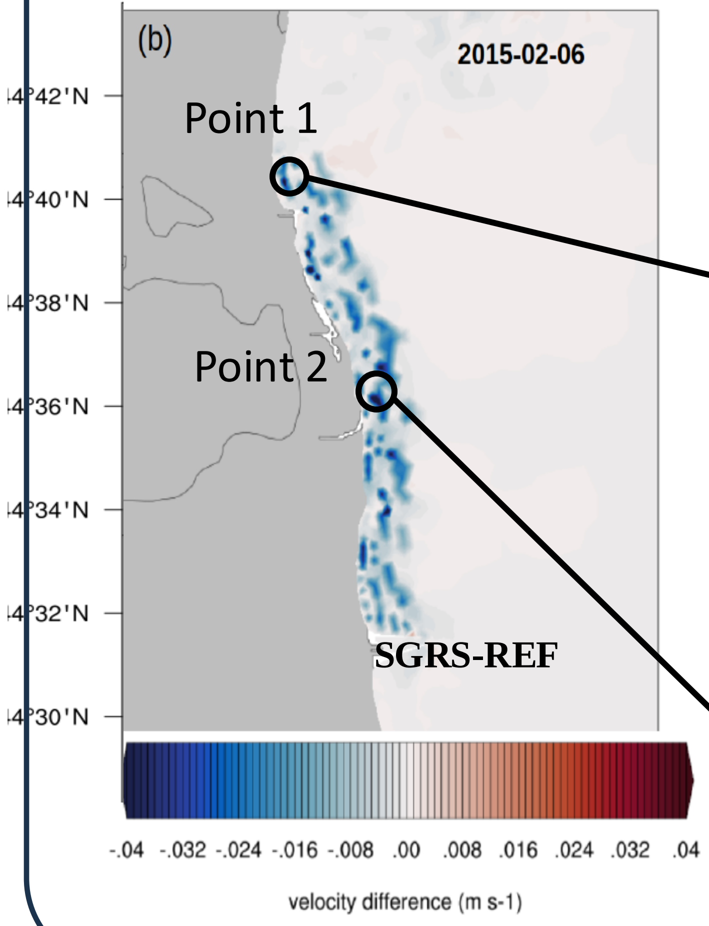


Emilia-Romagna

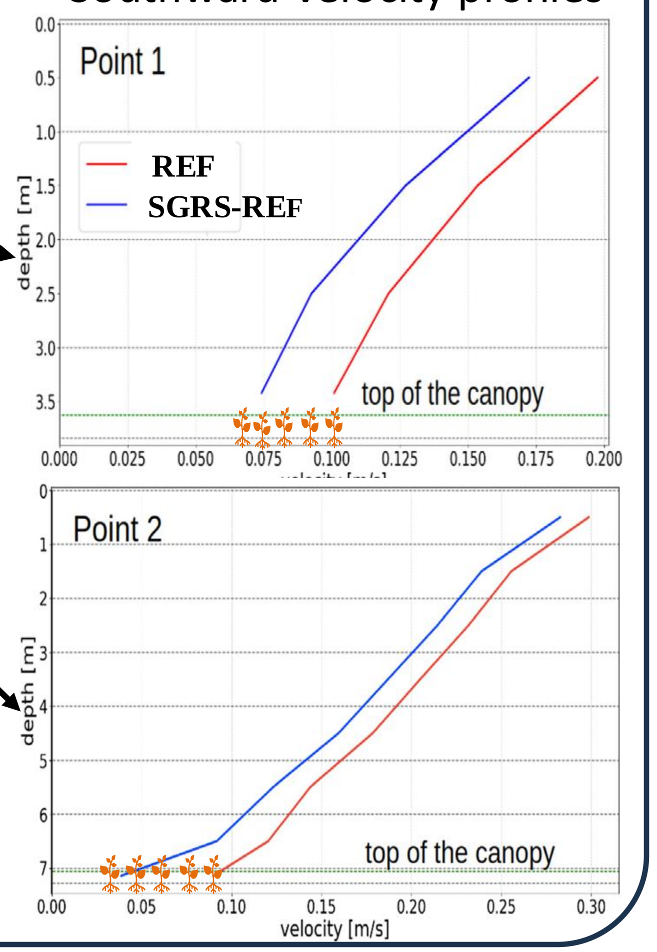




Seagrass effects spread also along the water column.



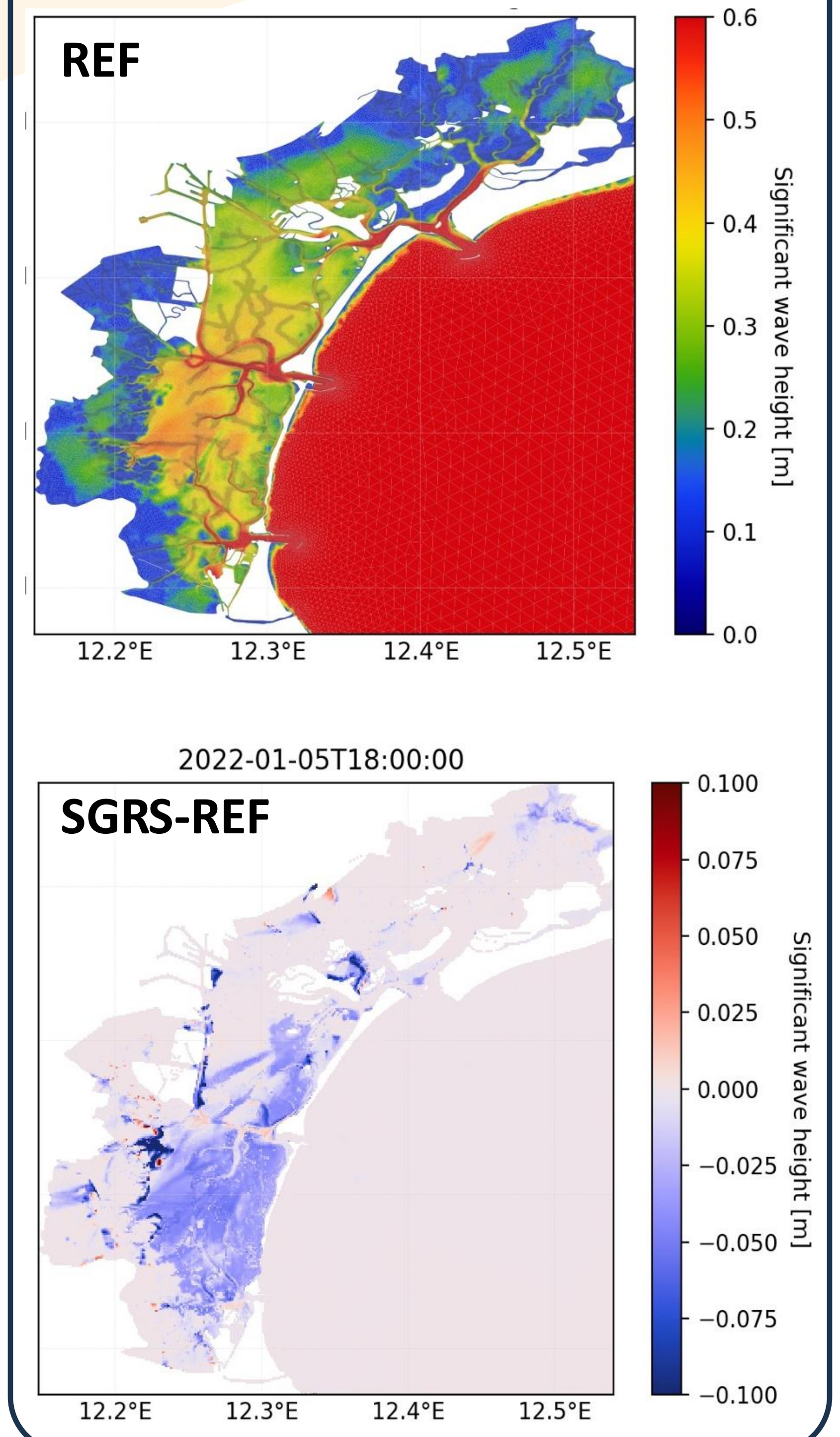
Southward Velocity profiles



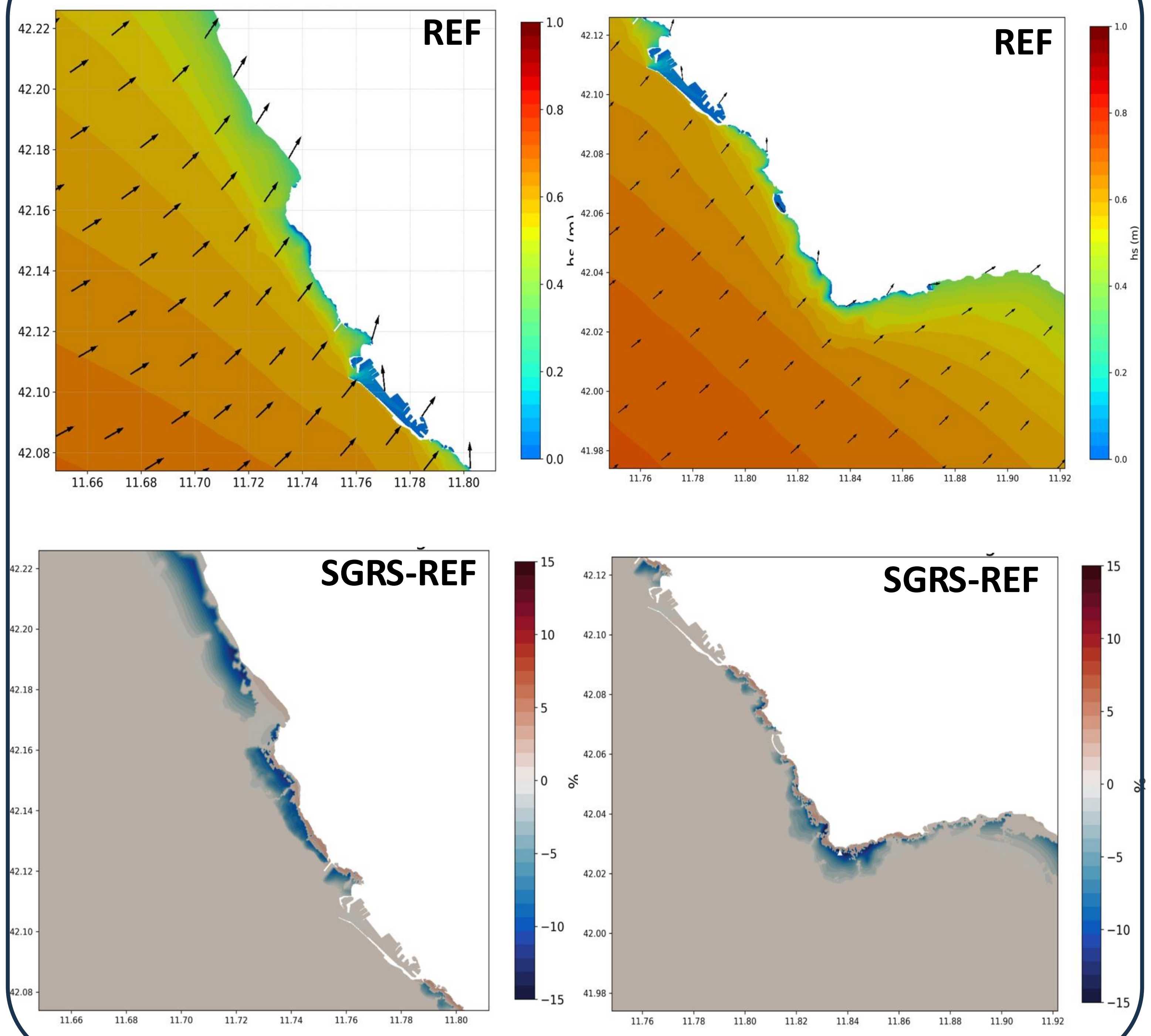
The presence of seagrass in the bottom layers acts as a **drag force dissipating the flow energy** and reducing the **velocity amplitude** up to **50-60 %** (In the bottom layers).

Significant Wave Height

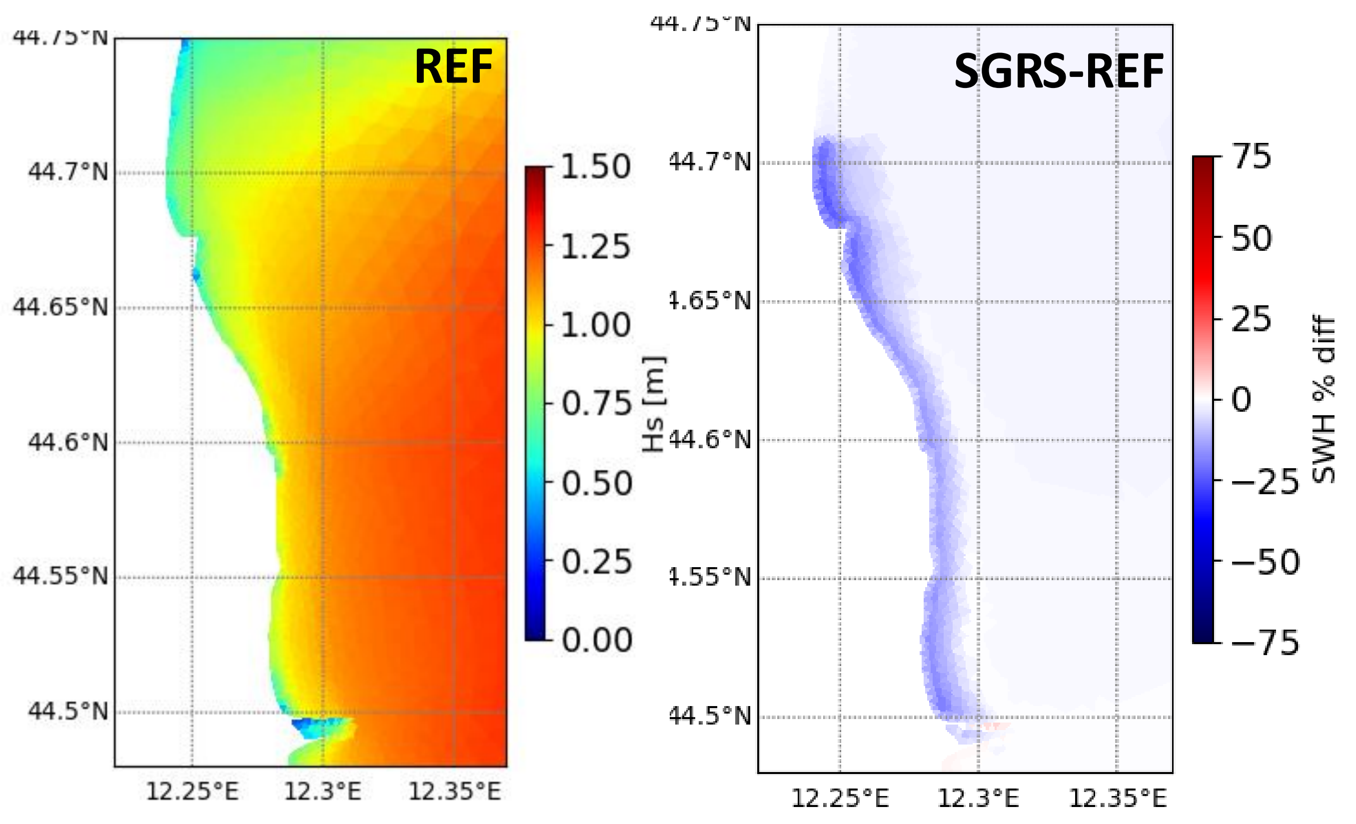
Venice Lagoon



Civitavecchia



Emilia-Romagna



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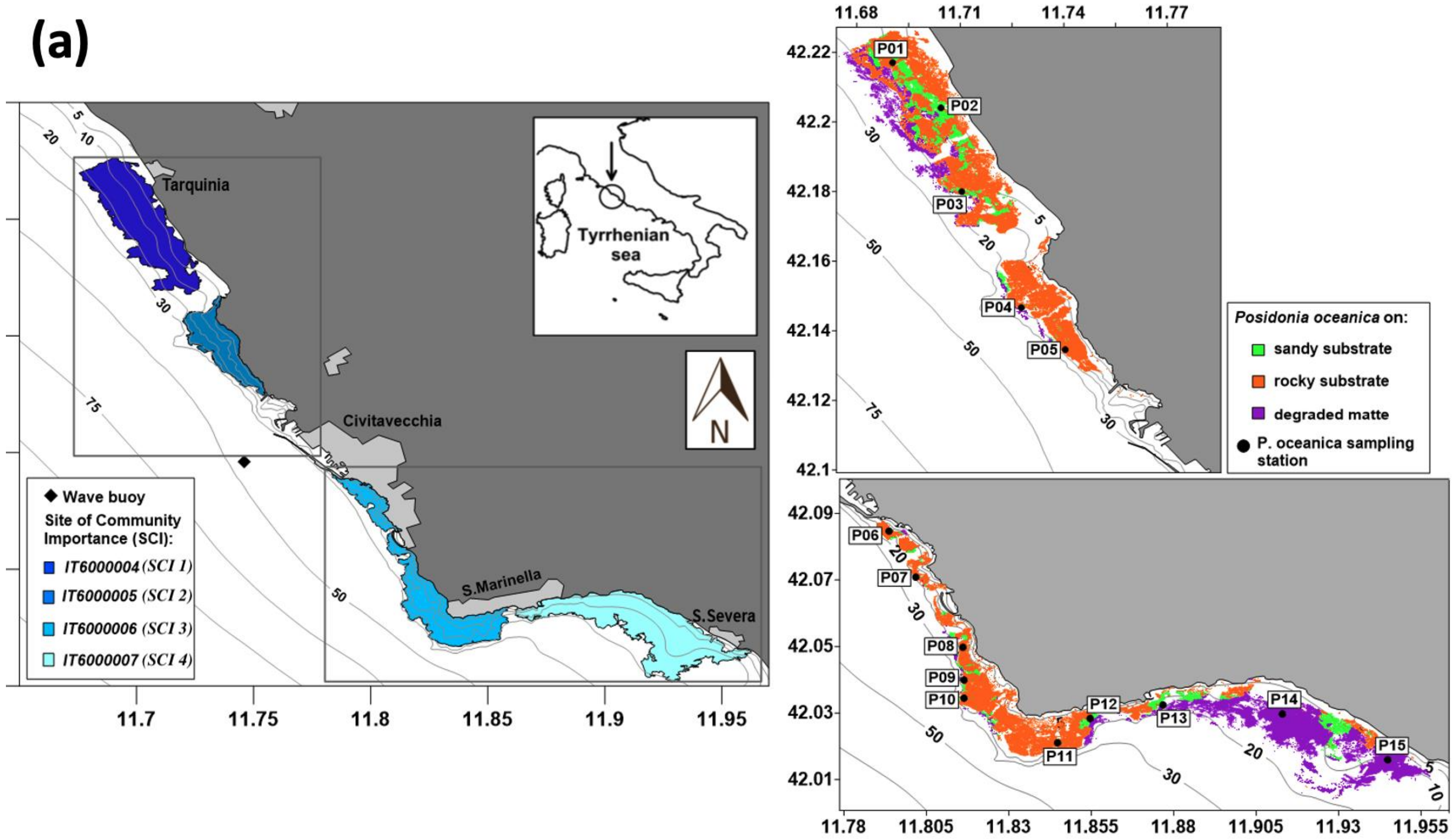
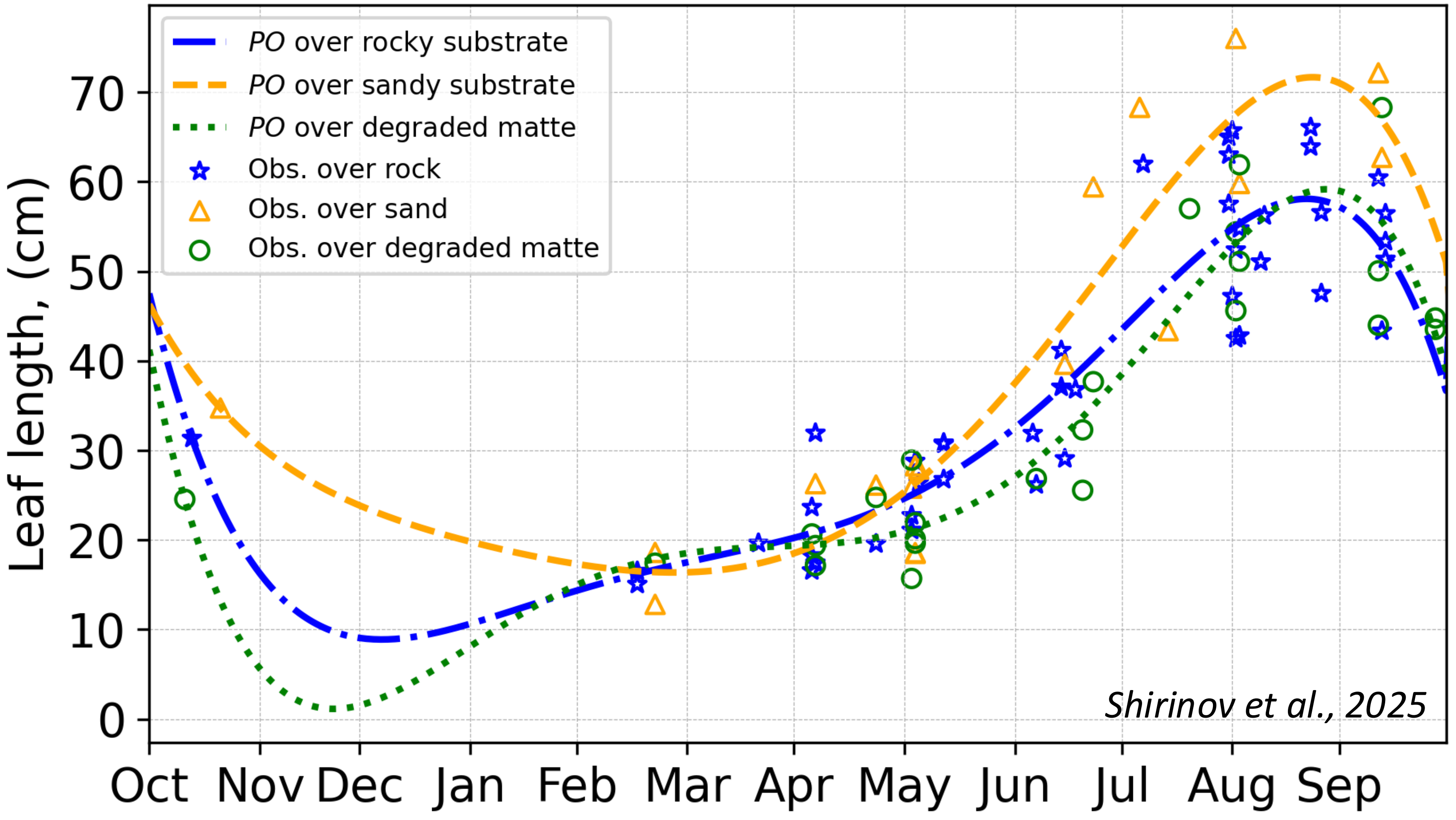
The comparison of **SGRS** and **REF** simulations show a **sensible decrease of the significant wave height** (**SWH**) due to the wave energy dampening effect of seagrass in all the domains considered with maximum reduction values between **10** and **15 %**.

Impact of Seagrass Seasonal Variability and Substrate

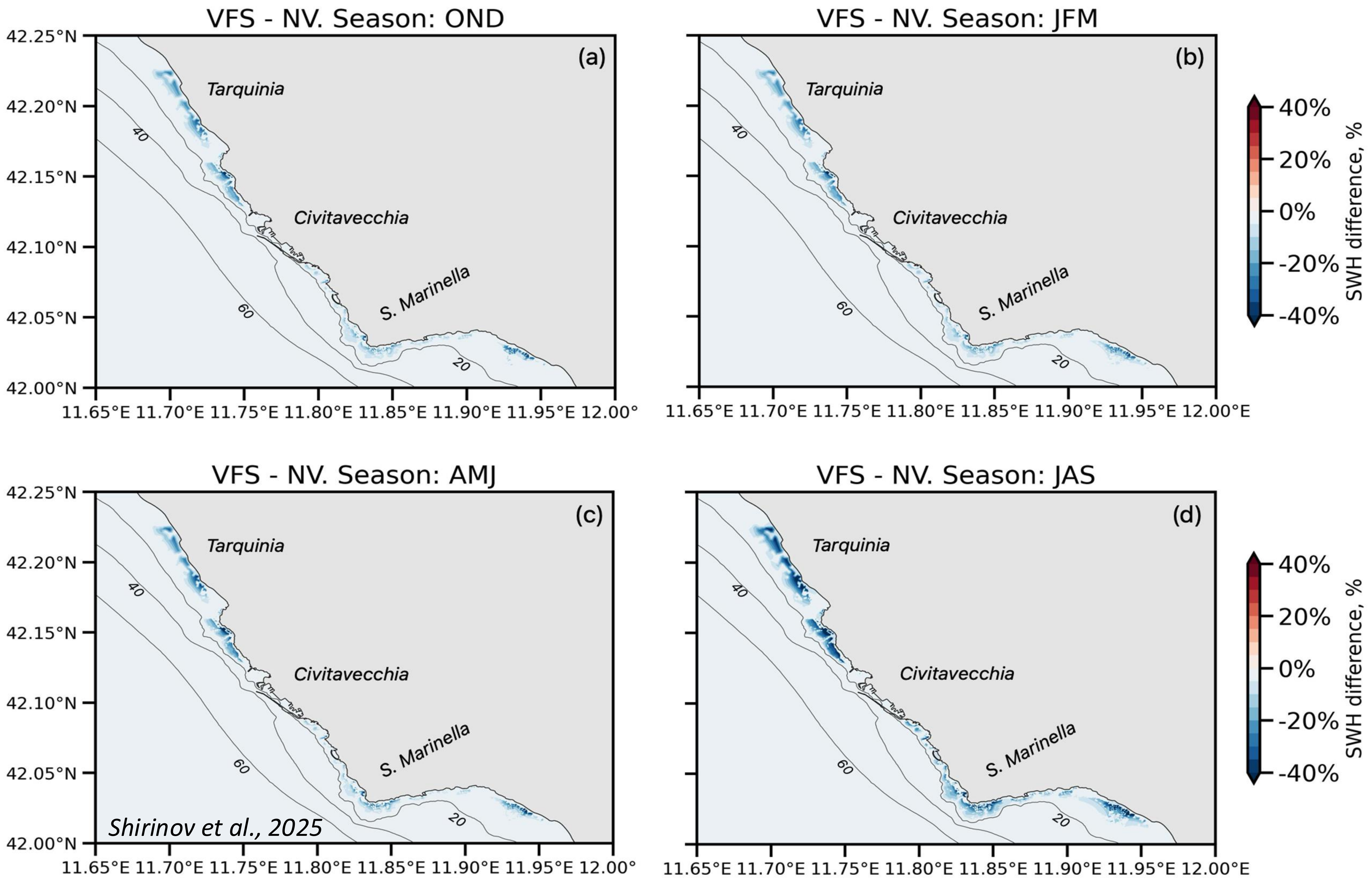
A further implementation of the **DTO** in Civitavecchia is based on **wave modelling** (WWIII) to study the effects of **seasonal variability** of seagrass leaves length on different **substrates** (rocky, sandy or degraded matte).





Observations of seagrass leaves length on different substrates are integrated in the DTO.

Impact of Seagrass Seasonal Variability and Substrate



The seasonal variability has a relevant influence on the wave energy damping

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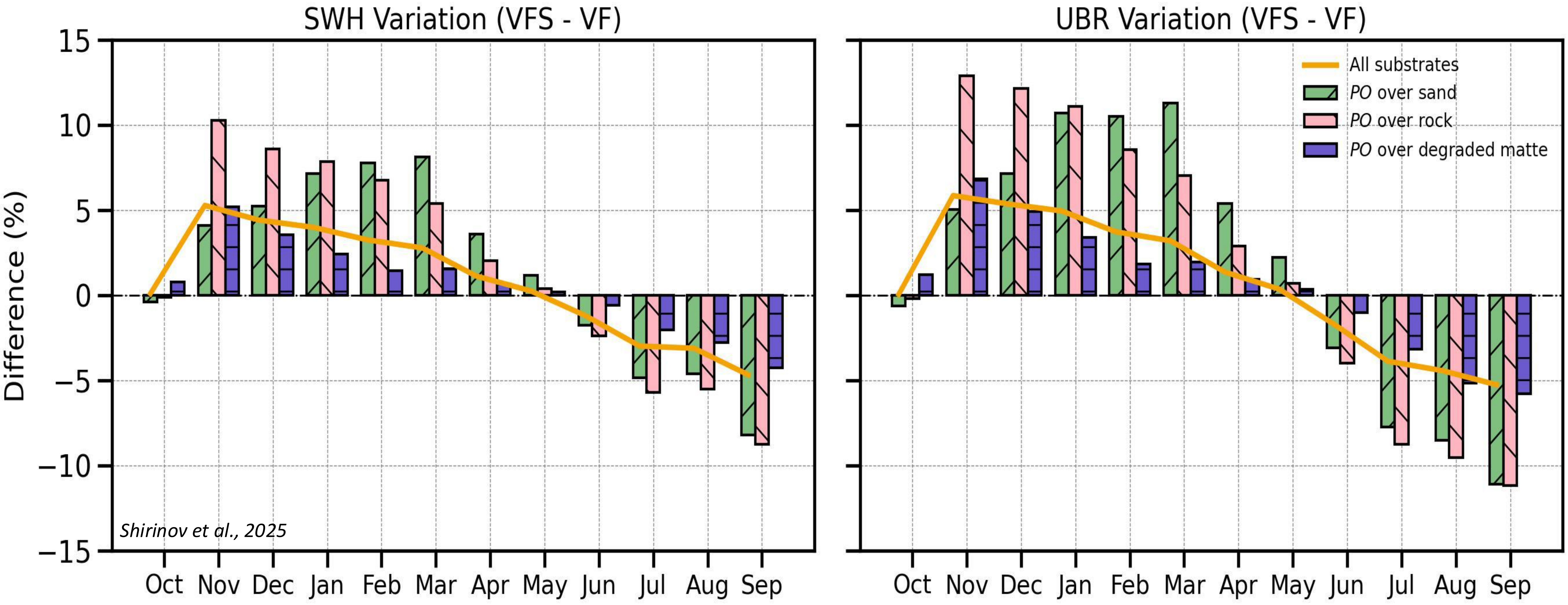
Impact of Seagrass Seasonal Variability and Substrate



a maximum of **10%** Amplification and reduction of wave damping in Summer and Winter respectively, with high variability due to the different substrates.

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4. Conclusions

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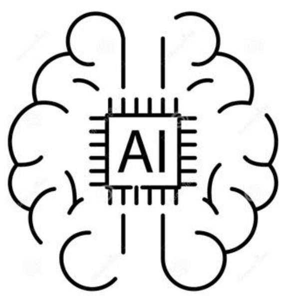
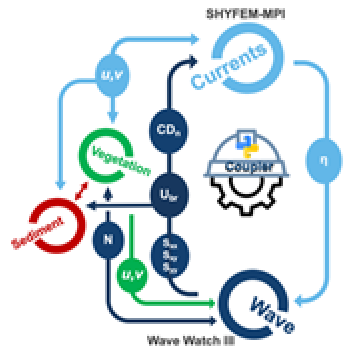
Concluding Remarks

A **DTO** can be used to quantitatively assess the **seagrass effectiveness** as an **NBS** against **the coastal hazard** due to **storm surges** in real coastal settings. Very high-resolution numerical model are used to build the DTO. **Observed data** can **integrate** into the DTO to improve the simulations, and new developments can enhance even more the realism of the simulations, going toward an integrated system where numerical tools and observations can provide reliable solutions.



INTEGRATING AI TOOLS

Artificial Intelligence (AI) tools will become an essential part of the development of **DTO** integrating **with numerical models** and **observations.**



MODEL DEVELOPMENT

Numerical models are still a fundamental tool for DTO. Further improving the physics, adding new processes (*e.g.* seasonal variability of seagrass leaves length) and model coupling may increase the reliability of a **DTO**.

NEW TECHNOLOGIES FOR SEAGRASS OBSERVATIONS

Observation are a fundamental part in the **DTO** development, both for model validation and as input data for the modelling part of the DTO (*e.g.* seagrass substrates). The development of new tools for seagrass mapping and observations (*e.g.* drones, satellite observations) can lead to a further improve of the DTO performance.

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THANK YOU!

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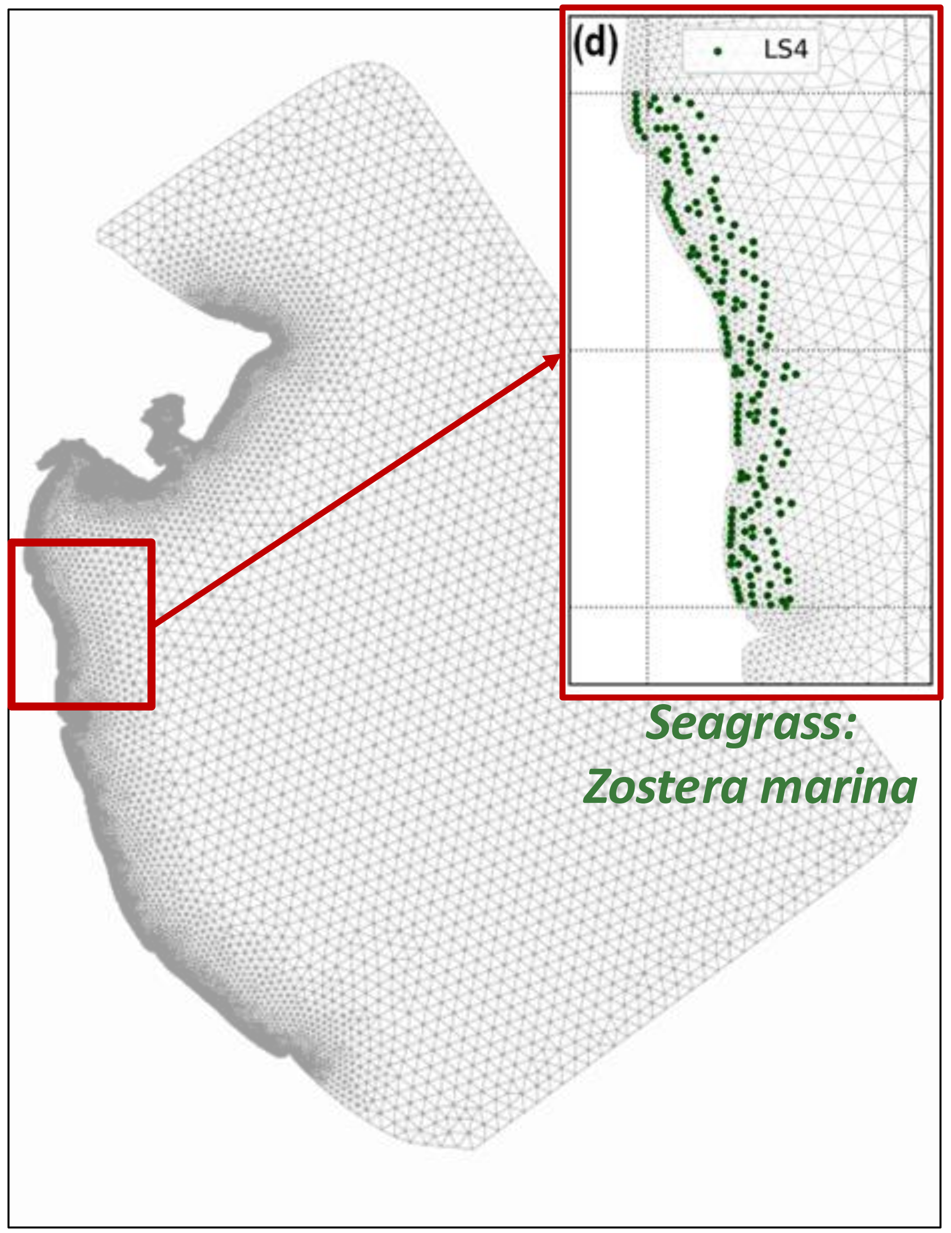
Ensemble DTO simulations

Emilia-Romagna



DTO

Ocean model

SHYFEM-MPI

Wave model

WaveWatch III ®

CNTR
(no seagrass)

What-if Scenarios

Table of Simulations		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*

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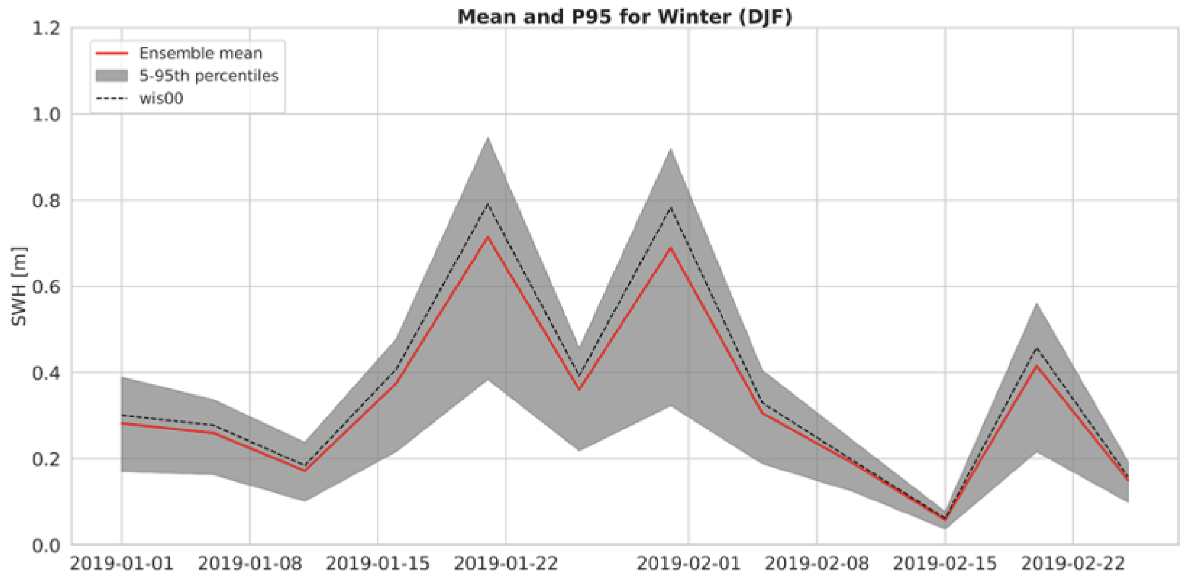
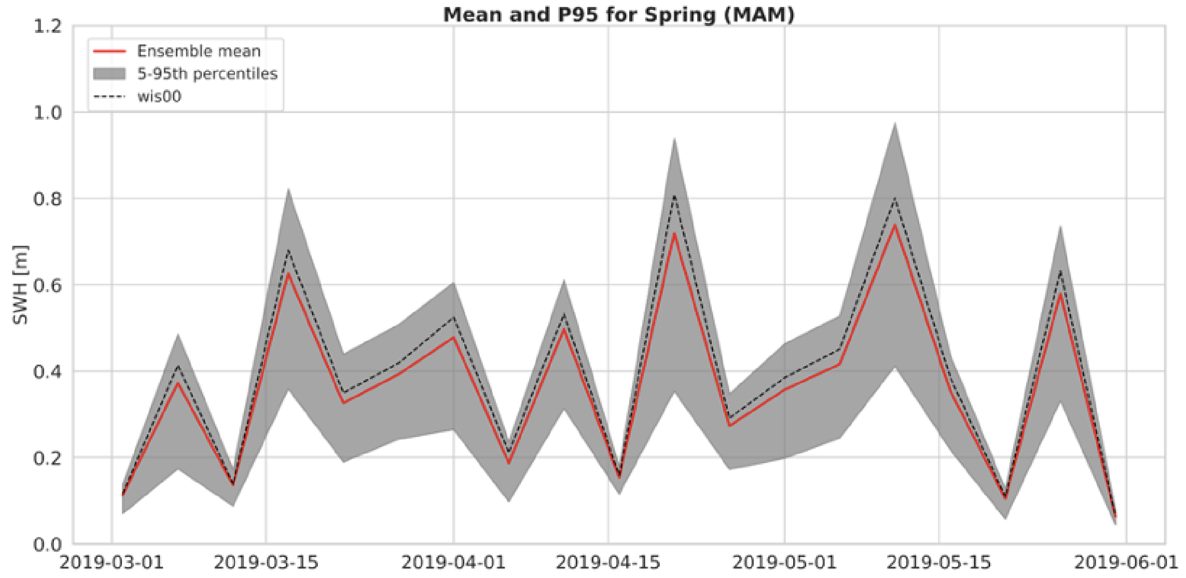
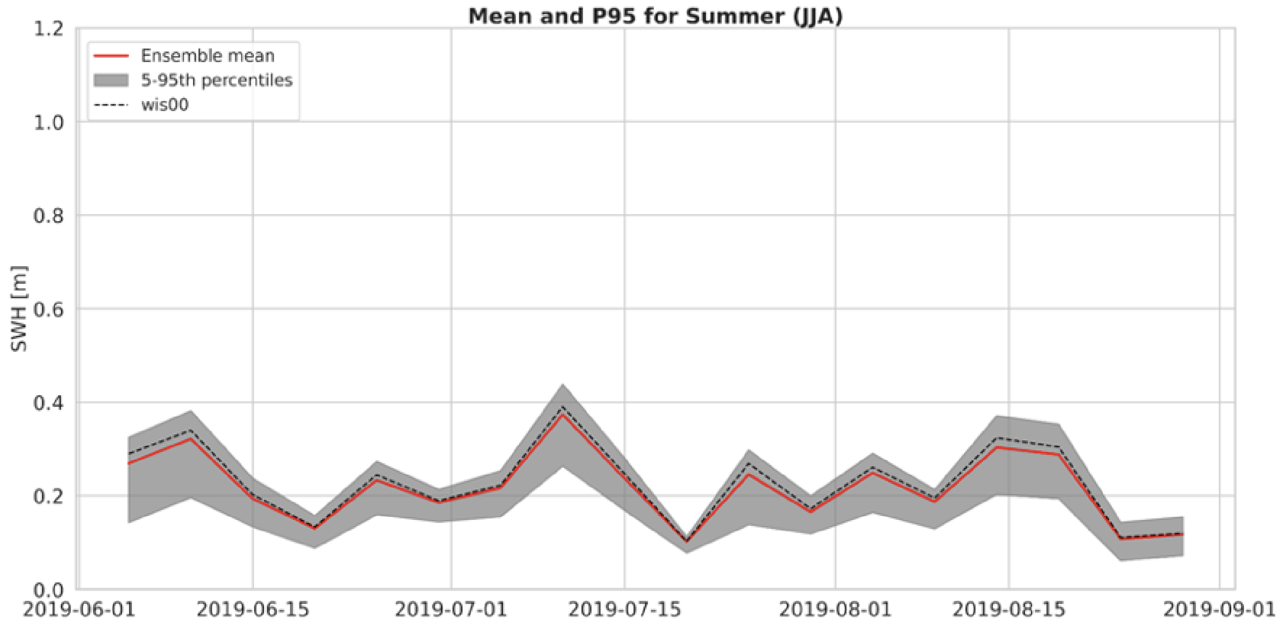
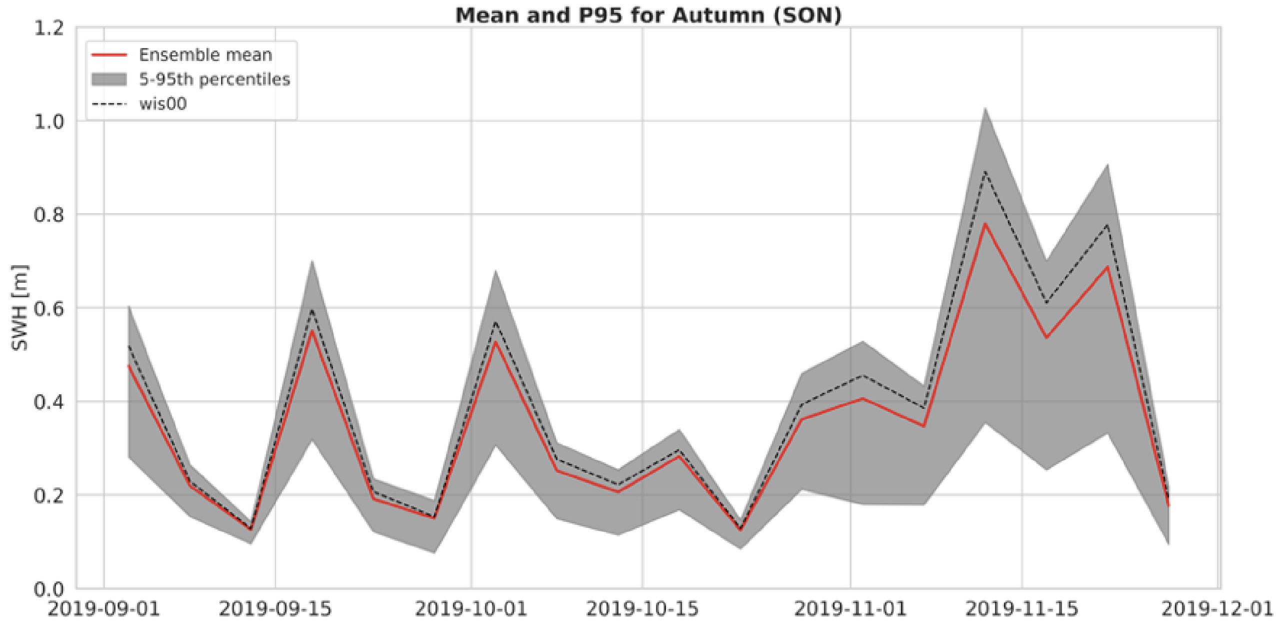
The **DTO** tools are used to generate an ensemble simulation where the seagrass characteristics such the length of the leaves (**L_v**), the width (**b_v**) and the shoot density (**N_v**) are varied to explore the **variability** of the effects of the seagrass on the wave and ocean variables.

Ensemble DTO simulations









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The **SWH** exhibits an high variability due to seagrass, especially in periods with high SWH values