



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DOTTORATO DI RICERCA IN
IL FUTURO DELLA TERRA, CAMBIAMENTI CLIMATICI E SFIDE SOCIALI
Ciclo 38

Settore concorsuale: 04/A4 - Geofisica

Settore scientifico disciplinare: GEO/12 - Oceanografia e fisica dell'atmosfera

CROSS-SCALE MODELLING OF COASTAL-OCEAN DYNAMICS: INTEGRATING
BENTHIC BOUNDARY LAYER INTERACTION, WAVE-CURRENT COUPLING, AND
SEDIMENT-DRIVEN MORPHODYNAMICS

Presentata da: Seimur Shirinov

Coordinatore dottorato:
Prof. Silvana di Sabatino

Supervisore:
Dr. Ivan Federico

Co-supervisori:
Prof. Nadia Pinardi
Dr. Lorenzo Mentaschi
Dr. Salvatore Causio

Esame finale anno 2026

What could possibly go wrong?

— *J.C.*

Abstract

Accurate prediction of coastal–ocean hydrodynamics and associated coastal hazards remains limited by the intrinsic complexity of representing multiscale, strongly coupled physical forcings that govern these nonlinear systems. The present work formulates, develops and validates an integrated numerical framework to resolve the emergent dynamics arising from such coupled interactions. Traditional single-process models often disregard essential cross-scale feedbacks among waves, currents, sediments, and benthic habitats, resulting in approximated representations of hydrodynamic and morphodynamic system responses. To address these gaps, a modular, multi-model framework was established through the progressive coupling of complementary numerical cores within a shared unstructured-grid architecture, enabling seamless representation of cross-scale exchanges, from open-ocean circulation to nearshore morphodynamics and benthic interactions. This integrative configuration enables the consistent exchange of momentum, mass, and energy across dynamic interfaces, thereby capturing the coupled feedbacks that govern coastal system evolution, from air-sea exchanges and wave-current interactions to biomechanical dissipation and sediment-driven bed adjustment, ultimately enhancing the physical fidelity and predictive skill of coastal-ocean simulations.

The framework was progressively integrated through successive coupling stages, systematically incorporating physical processes to resolve the full complexity of these interactions. First, a dynamically consistent two-way wave-circulation coupling, exchanging sea-state dependent momentum fluxes, radiation stresses, Doppler shift, dynamic water depth, and effective wind speed was established through idealized domains, and further applied to an extreme event driven by a Mediterranean tropical-like cyclone. The wave-induced surge contribution to the total water level, excluding unresolved swash-zone dynamics, and its impact on upper-ocean thermal structure were then quantified, highlighting the critical importance of coupled modelling during

extreme storms. The framework was subsequently extended to incorporate the biomechanical influence of the marine benthic boundary layer on wave transformation through an improved bottom-dissipation parameterization. Numerical experiments in the Balearic Islands (Mallorca) and along the Civitavecchia coastline in the Tyrrhenian Sea quantified wave attenuation and changes in spectral wave characteristics induced by the flexible representation of aquatic meadows and their phenological cycles, emphasizing the coastal protection services provided by benthic vegetation. Finally, a three-dimensional sediment transport and morphodynamics module was implemented, incorporating unified wave-current bedform roughness and intra-wave transport formulations, universal settling velocity, and Exner-based bed evolution feedbacks to hydrodynamics. The module was benchmarked against the state-of-the-art and finite-element coastal models on idealized domains, demonstrating robust performance across diverse flow regimes, geometries and forcing fields, and reproducing characteristic erosion-deposition patterns. The real-world application at the Tiber River delta further captured river-plume sediment dispersal and offshore concentration patterns, showing agreement with both satellite observations and in-situ measurements.

Future work and existing limitations are outlined to inform subsequent model refinement and applications. The integrated system developed in this study provides a transferable framework for estimation of compound coastal hazards and contributes a concrete step toward more comprehensive representation of complex coastal-ocean dynamics.

Contents

Abstract	2
1 Introduction	18
1.1 Problem statement and rationale	19
1.2 Storm surge, wave extremes and coastal erosion	19
1.3 Multi-model integration for coastal-ocean dynamics	21
1.3.1 Waves and circulation	22
1.3.2 Benthic boundary layer	23
1.3.3 Sediment transport and morphodynamics	24
1.4 Thesis objectives	26
2 Coupling ocean currents and waves for seamless cross-scale modelling	29
2.1 Physics of coupled systems and the scope	29
2.1.1 Storm-induced coastal hazards and Mediterranean cyclones	30
2.1.2 Medicane Ianos and the objectives	31
2.2 The modelling framework	33
2.2.1 Circulation modelling	33
2.2.2 Wave modelling	36
2.2.3 Coupling methodology	36
2.3 Validation of the coupled model	40
2.3.1 Planar beach	40
2.3.2 The coastal inlet	42
2.4 Wave-circulation fields during Medicane Ianos	48
2.4.1 Set-up of the model	49
2.4.2 Synoptic overview and results	51

2.4.2.1	Effects of circulation on waves	53
2.4.2.2	Effects of waves on circulation	56
2.4.2.3	Computational performance and parallel reproducibility . . .	63
2.5	Discussion	64
3	Modelling vegetation-induced wave attenuation	66
3.1	Concepts of wave-canopy dynamics and objectives	67
3.1.1	First experimental and numerical models	68
3.1.2	Flexible formulation and seasonal variability	69
3.1.3	The present study approach	71
3.2	Modelling framework	72
3.3	Model validation	75
3.4	The Civitavecchia case study	80
3.4.1	Model setup	82
3.4.2	Observational data	86
3.5	Findings and interpretation	88
3.5.1	Wave field analysis	88
3.5.2	Model performance analysis	89
3.5.3	Seagrass induced wave attenuation	93
3.5.3.1	VFS vs. NV: Wave attenuation by <i>P. oceanica</i> over different substrate types and SCIs	95
3.5.3.2	VFS vs. VF: The contribution of seasonal variability of sea- grass leaf length	97
3.5.3.3	Seasonal wave attenuation maps	98
3.6	Discussion	98
4	Wave- and currents-driven sediment transport and morphodynamics	104

4.1	Theory and implementation	104
4.1.1	Dynamics of the bottom boundary layer	105
4.1.2	State of the art	106
4.1.3	Concept of sediment transport modelling	107
4.1.4	Challenges and study outline	108
4.2	Methodology	109
4.2.1	Model implementation and limitations	109
4.2.2	Governing equations	110
4.2.2.1	Advection-diffusion of suspended sediments	111
4.2.2.2	Seafloor evolution	112
4.2.2.3	Free surface	113
4.2.2.4	Radiation stresses	113
4.2.2.5	Sediment motion initiation criteria	114
4.2.2.6	Bed roughness	116
4.2.2.7	Bottom friction	117
4.2.2.8	Shear velocity computation	118
4.2.2.9	Vertical sediment-mixing coefficient	119
4.2.2.10	Bedload transport	119
4.2.2.11	Rouse concentration profile	121
4.3	Experiments	123
4.3.1	Tidal inlet	123
4.3.1.1	Inlet domain and model set-up	124
4.3.1.2	Inlet test results and inter-model comparison	125
4.3.2	River channel	132
4.3.2.1	River domain and model set-up	133
4.3.2.2	River results and inter-model comparison	133

4.3.3	Fiumicino case study	137
4.3.3.1	Data collection and processing	138
4.3.3.2	Model setup	140
4.3.3.3	Validation against satellite-derived suspended sediments	141
4.3.3.4	Comparison with the CTD casts	145
4.3.3.5	Physical drivers of seasonal sediment budget	147
4.4	Discussion	151
5	Concluding remarks	154
5.1	Synthesis and research trajectory	154
5.2	Framework advancement and physical insights	155
5.3	Limitations and pathways toward enhanced fidelity	157
5.4	Advancing toward predictive capability	159
	Acknowledgements	161
	References	162

List of Figures

- 1.3.1 Schematic representation of the multi-model integration framework. The arrows indicate the exchange of scalar and vector terms between different model components. The dashed arrow indicates the yet unestablished interaction, that is not considered in this work. η is the sea surface elevation, τ_b is the bottom friction, $\mathbf{u}$ is the current velocity, H_s is the significant wave height, f_p is the peak frequency, θ is the wave direction, $\mathbf{u}_b$ is the near-bed wave orbital velocity, ζ is the bed elevation, $\delta\zeta$ is the bed level change, ΔT is the air-sea temperature difference, $\mathbf{S}_{xy}$ is the radiation stress tensor (S_{xx}, S_{xy}, S_{yy}), and C_D is the neutral drag coefficient. 22
- 2.0.1 Schematic representation of the two-way coupling between SHYFEM-MPI and WW3 models. It represents the core wave-current interaction layer that builds the foundation for the multi-model integration framework (Figure 1.3.1). 29
- 2.2.1 The coupling procedure between SHYFEM-MPI and WW3. When the simulation starts, models exchange information after the first time step (e.g. $\Delta t_0 = 300s$), then exchange every $\Delta t_{coupling}$ (e.g. every 1h). SHYFEM-MPI sends sea level (η), current fields ($\mathbf{u}, \mathbf{v}$) and air-sea temperature difference (ΔT) to WW3. WW3 sends neutral drag coefficient (C_{Dn}) and radiation stresses (S_{xx}, S_{xy}, S_{yy}) to SHYFEM-MPI. 38
- 2.3.1 Numerical domain and bathymetry of the two idealized benchmarks: the planar beach (a) and the tidal inlet (b). Dashed red lines show the transect from point 1 to point 2, where the numerical solutions were assessed. The dotted box in (b) denotes the area magnified and is shown later in the 2.3.3. 40

2.3.2	Planar beach testcase: comparison between model and analytical solution along the transect 1-2 shown in Figure 2.3.1(a). The testcase verifies the C-WF simulation, assessing the role of wave set-up (via radiation stresses) to the total water level.	42
2.3.3	Wave-forced coastal inlet at steady condition: significant wave height for the wave-only simulation (a) and for the two-way wave-currents coupled simulation (b); currents for the wave-to-current forced simulation (c) and for the two-way wave-currents coupled simulation (d).	45
2.3.4	SWH (a) and water elevation (b) of the transects along section 1-2 as indicated in Figure 2.3.1(b). The figures replicate the Cobb and Blain (2002) simulations: in (a) we compared W-0 and W-C simulations, while in (b) we compared C-WF with W-C experiment.	46
2.3.5	Magnification (at 17-23 km) of the water level along the transect 1-2 shown in Figure 2.3.1(b) for configuration C-0 and W-C in a tidally-driven framework at the ebb (a) and flood (b) phase.	47
2.4.1	Spatial unstructured-grid and bathymetry for the Ionian Sea (b) used for the Ianos Medicane simulation, with an enlarged view on refined areas of affected area (a).	50
2.4.2	Maps of significant wave height (a), sea level (b), sea surface temperature (c) and surface circulation (d) on 2020-09-16 18:00 UTC (peak time in open ocean) for the entire domain from two-way coupled simulation.	52
2.4.3	Maps of significant wave height (a), surface circulation (b) and sea level (c) on 2020-09-18 06:00 UTC (peak time in coastal zones of Greece) for the Greek coastal areas from two-way coupled simulation (W-C).	54

2.4.4	Maps of SWH against satellite altimeter (Jason3, Saral-Altika, Sentinel-3b) tracks (inset circles) for the W-C configuration (a) (b) (c). SWH along-track comparison between the two model configurations and satellite tracks is reported in (e), (f) and (g).	55
2.4.5	(a) SWH scatter plot for the W-C configuration is shown, with colors indicating the plot density of occurrence. The black line represents the best-fit line, while the red line denotes the linear regression of the data. (b) Statistics (Root Mean Squared Error – RMSE, Bias, Scatter Index – SI, Pearson’s correlation coefficient – ρ , and the slope of the fit) are summarized and expressed in meters, providing comparisons for the W-C and W-0 configurations as well as the percentage difference between them.	56
2.4.6	Maps of drag coefficient (C_d) at the peak event in open ocean (2020-09-16 18:00). (a) Drag coefficient computed by WW3 in the W-C experiment. (b) Drag coefficient computed via Hellerman and Rosenstein (1983) in the C-O experiment. (c) Difference between (a) and (b).	58
2.4.7	Sea surface temperature anomaly [$^{\circ}\text{C}$] between 19th Sept. (after Ianos) and 14th Sept. (before Ianos) from satellite (a), two-way coupled model W-C (b), and SST difference between the anomaly of W-C and C-0 (c). The black path represents the Medicane Ianos path identified as minimum sea level pressure location every 6 hours. In panels (a) and (b) the colorbar range is set to $[-4, 4^{\circ}\text{C}]$ to better highlight the footprints pattern, even though the difference reached -5°C	59
2.4.8	Anomaly Temperature difference between W-C and C-0 for the Medicane Ianos passage over the central Mediterranean Sea. Black lines refer to the mixed layer depth for W-C (solid line), and C-0 (dashed line). The x-axis corresponds to the locations shown in Figure 2.4.7(a).	60

2.4.9	Timeseries of TWL for C-0 and W-C configurations. In plot (a) upper panel, the model are compared with observed data at Katakolon tide gauge -TG (in dashed gray). In the plot (b) bottom panel, the model configurations are compared at the Kourouta beach. The shaded yellow area highlights the two days impacted by the Medicane induced surge. Plot (b) highlights the wave setup (in red) and setdown (in blue), computed as the TWL difference between C-0 and W-C. Additionally, it shows the location of the timeseries (in plot a), as well as the mean wave direction represented by vectors.	62
2.4.10	Error evolution over a 7-day simulation for u and v components and SWH, using 144 and 216 cores.	64
3.0.1	The benthic boundary layer represented through wave-vegetation interaction mechanisms forming a part of the multi-model framework (Figure 1.3.1). The vegetation-induced drag is provided through advancing the rigid formulation onto (i) flexible one, introducing blade bending mechanisms, and further (ii) seasonal, with intra-annual variability of the canopy height. The latter is informed by in situ observations.	67
3.3.1	A Cala Millor case study domain and bathymetry customized from Infantes et al. (2012), with location of mooring data. O denotes offshore moorings, while N denotes nearshore moorings. Green mesh elements indicate elements with vegetation, while yellow elements do not include vegetation at the bottom. The dashed line represents the transect N - O analyzed later.	77
3.3.2	Significant wave height (SWH) timeseries comparison for <i>no_veg</i> (no vegetation), <i>veg_rigid</i> (rigid vegetation) and <i>veg_flex</i> (flexible vegetation) experiments against nearshore and offshore moorings in Figure 3.3.1.	77

3.3.3	(a) Map of SWH for <i>veg_flex</i> configuration and (b) SWH profiles for the three configurations (<i>no_veg</i> , <i>veg_rigid</i> and <i>veg_flex</i>) along the transect N-O (as indicated in Figure 3.3.1) at the event peak of 2009-07-17 - 23:00.	79
3.4.1	Map of the area of Civitavecchia with bathymetry, Sites of Community Importance (SCI), observations used in the study and distribution of the <i>P. oceanica</i> over the different substrate types (<i>P. oceanica</i> on rock, <i>P. oceanica</i> on sand and matte, and degraded matte with <i>P. oceanica</i>). (b) Mesh of the computational domain with enlarged views in the vicinity of the Civitavecchia harbour.	81
3.4.2	<i>P. oceanica</i> leaf length variation throughout the year, showing seasonal observations alongside fitted growth curves.	87
3.5.1	Maps (zoomed over the coastal area) of annual mean (a,b) of VFS and NV configurations, and seasonal (OND, JFM, AMJ, JAS) mean (c, d, e, f) SWH (1 Oct 2016 - 30 Sept 2017) including flexible vegetation and seasonality effect (VFS). The wave buoy position is indicated by the star marker.	90
3.5.2	Comparison of the wave model results with the buoy data (Figure 3.4.1a) in terms of timeseries (a) and a scatter plot (b). In plot (b), the dash-dot black line represents the perfect correlation for the reference, while the solid red line shows the model fitting. A statistical summary is also provided.	91
3.5.3	Heatmap of SWH and wave direction relative bias (dimensionless), with the relative bias formulation described in Roelvink et al. (2009).	91
3.5.4	Maps (a, b) of wave orbital excursion (A_w) with the $L-ratios$ over the vegetated areas; (c) the domain-averaged (over vegetation only) monthly mean L-ratios.	94
3.5.5	Mean monthly H_s and U_b percentage reduction (VFS experiment) for <i>P. oceanica</i> over different substrates (a,b), and four SCIs (c,d), averaged across vegetated points in the mask.	96

3.5.6	Timeseries of mean monthly H_s and U_b percentage difference between VFS and VF simulations across substrate types $((H_{VFS} - H_{VF})/H_{VF} \times 100)$. Bars indicate the average differences over vegetated points for each substrate, while the solid orange line represents the weighted average across all vegetated areas in the domain.	97
3.5.7	Maps (zoomed over the coastal area) of seasonal (OND, JFM, AMJ, JAS) mean SWH attenuation (VFS - NV).	99
3.6.1	The impact of vegetation on wave characteristics. (a) Transect line at SCI 2 site, near P05 sampling station; (b) Wave steepness and mean wavelength profiles (annual means) along the transect line, where the shore end is the origin of the x-axis.	100
4.0.1	Schematic representation of the two-way coupling between hydrodynamics (waves and currents) and sediment transport/morphodynamics. The exchange fields and their corresponding symbols are detailed in Figure 1.3.1.	105
4.3.1	Tidal inlet domain with top-down look at the bathymetry map (a), and a profile along A-B transect (b). Arrows indicate the flow forcing direction, characterised by the tidal and wave forcing at the open boundary.	125
4.3.2	Bed evolution (ζ) comparison between SHYFEM-MPI (left) and ROMS (right) adapted from Warner et al. (2008). The dashed frames indicate similar erosion and deposition patterns corresponding between the two models.	126
4.3.3	Ebb and flood tide phases: sea surface elevation (η) and current vectors $\mathbf{u}$ comparisons between SHYFEM-MPI (right) and FVCOM (left) adapted from Wu et al. (2011). The dashed boxes indicate eddy formations corresponding between the two models.	128

4.3.4	Thetis model comparison: velocity field ($\mathbf{U}$), suspended sediment concentration (C_s), bed elevation (ζ), and sea surface elevation (η). The last row provides differences between the two models and the statistical metrics.	129
4.3.5	Suspended sediment concentration (SSC) profiles at along the A-B transect (see Figure 4.3.1). The blue dash-dotted line indicates the free surface elevation. The solid black line indicates the evolved bed elevation at an indicated hour, and the dashed black line the initial bed elevation for the reference.	131
4.3.6	Sea surface elevation (η) differences between the two experiments with and without feedback from morphodynamics at ebb (left) and flood (right) tides, given by the bed elevation change ($\partial\zeta/\partial t$) component in Eq. 4.2.8.	132
4.3.7	River bend domain with the arrow indicating the flow direction. On the right side are a few experimental (a,b,c) results of Yen and Lee (1995), showing the erosion and deposition patterns, in terms of scaled bed elevation changes ($\Delta\zeta/\zeta$).	134
4.3.8	Scaled bed elevation changes ($\Delta\zeta/\zeta$) with the slope and secondary currents corrections at $t = 5 \text{ h}$ of the simulation for the Thetis (left) and SHYFEM-MPI (right) models.	135
4.3.9	Scaled bed elevation changes ($\Delta\zeta/\zeta$) at the end of the simulation without (a) and with (b) secondary flow effects. Right panel shows the results of Thetis model and the left panel the SHYFEM-MPI results.	136
4.3.10	(a) Suspended sediment concentration (SSC), and (b) grain size distribution (GSD) at the Tiber river mouth. The quadratic formulation used to compute SSC is based on in-situ measurements and is depicted in panel (a), along with conventionally used power-law formulations for comparison. The panel (b) shows the GSD sampling tracks during field campaigns, while the fractions of different sediment classes composing the bed morphology is given in terms of the their sizes and corresponding averages over the sampling tracks (second box).	139

4.3.11	Fiumicino model domain, bathymetry and unstructured grid (top-right framed box). The isobars indicate the depth.	141
4.3.12	Comparison of modelled and satellite-derived suspended sediment concentration (SSC) on 14 February 2021 at 10:00 (CET). The first row shows the SSC maps near the Tiber river mouth for the model (left) and satellite (right). The second and third rows show the SSC transect profiles extending from the two river mouths to the offshore area.	143
4.3.13	Vertical profiles of suspended sediment concentration (SSC) at two locations along the transect lines on 14 February 2021. The second and third rows depict the zonal (U) and meridional (V) velocity components.	145
4.3.14	Comparison of modelled and measured suspended sediment concentration (SSC) profiles from CTD casts at various stations. The map illustrates the spacial distribution of CTD stations (left), with the modelled and measured SSC values indicated by the color scale, and summarised in the annotation boxes. The vertical profiles of SSC (right) compare the model (red) with CTD measurements (blue) at each corresponding station. The statistical metrics are provided for each station.	146
4.3.15	Seasonal mean suspended sediment concentration ($SSC, kg/m^3$) along the central Lazio coastline near the Tiber River mouth, averaged over late summer (Aug–Sep 2020), autumn (Oct–Nov 2020), winter (Dec 2020–Feb 2021), and spring (Mar–May 2021). The maps illustrate the seasonal variability in plume extent and dispersion under changing river discharge and hydrodynamic forcing.	148
4.3.16	Empirical Orthogonal Function (EOF) analysis of suspended sediment concentration ($SSC, kg/m^3$) seasonal variability. The EOF1 mode explains 50–80% of the variance, representing the dominant seasonal pattern of sediment dispersal, with higher concentrations and broader plumes during winter months.	149

-
- 4.3.17 EOF analysis of bottom orbital velocities (m/s) across seasons. The leading mode (EOF1) explains over 90% of the total variance, representing a strongly coherent spatial pattern of wave-induced forcing for sediment resuspension. . . . 149
- 4.3.18 EOF analysis of surface currents (m/s) at the Tiber River delta. The top row illustrates the spatial distribution of the first mode (EOF1), explaining 30–46% of the variance; the bottom row illustrates the second mode (EOF2), explaining 10–25% of the variance. 150

List of Tables

2.3.1	Configurations and nomenclature for the numerical setup used in this study. . . .	41
2.4.1	Datasets used in this study.	51
2.4.2	Summary of the average differences in the investigated variables after a 7-day simulation using 144 and 216 cores.	63
3.2.1	List of symbols used in Section 3 and their corresponding units of measurement.	73
3.3.1	Numerical model parameters used for Infantes et al. (2012) case study.	75
3.4.1	Description of the numerical experiments.	83
3.4.2	Vegetation parameters for different substrates of <i>P. oceanica</i> meadows with ini- tial and averaged over the simulation period (annual mean) leaf length values, derived from field sampling within the study area.	84
3.4.3	Growth curves coefficients for the considered <i>P. oceanica</i> traits in the study. . .	85
3.5.1	Monthly mean H_s and U_b over vegetation area and their differences for the three experiments in Table 3.4.1.	92
4.3.1	Model parameters for tidal inlet test case.	126
4.3.2	Parameter values for the meander test case. Source: Clare et al. (2021).	135

Chapter 1

Introduction

From the first numerical attempt by Richardson (1922) to solve Bjerknes's primitive equations, the foundations of modern numerical weather prediction were laid. Though his six-hour, hand-calculated forecast was impractical, it established the concept. With digital computers, Charney's team (Charney et al., 1950) produced one of the first forecasts on the ENIAC using a simplified barotropic model (Platzman, 1979). Phillips (1956) soon advanced this with a multi-layer hemispheric model, proving the feasibility of operational forecasting. In the 1960s, numerical methods extended to the ocean and later to wave modelling with spectral, third-generation formulations (Hasselmann et al., 1973). Together, these developments formed the basis of today's coupled atmosphere-ocean models. Since then, atmospheric and oceanic models have evolved dramatically, driven by exponential growth in computational power, progressing from early vector supercomputers to massively parallel multicore architectures and unstructured grids (Chen et al., 2003; Balaji et al., 2017). Concurrent innovations in software were essential for harnessing this capability, including the development of parallel programming paradigms, high-performance scientific libraries, and efficient numerical solvers (Bauer et al., 2015). These hardware and software advances have enabled models to progress from idealized representations to comprehensive Earth system models, achieving increasingly fine spatial and temporal resolutions while representing a suite of coupled physical processes (Eyring et al., 2016).

1.1 Problem statement and rationale

Despite the advances in modelling techniques and computational power, many challenges remain. Coastal–ocean environments are governed by strongly nonlinear, multiscale forcing among atmosphere, circulation, tides, waves, sediments, biogeochemical feedbacks and human interventions. Treating any of these drivers in isolation obscures feedback loops that affect stress fields, modulate bottom boundary layer structure, alter sediment availability, and shift total water level components. Fragmented approaches can lead to biased attribution of erosion, flooding, morphodynamic adjustment, wave energy transformation, and turbulent mixing, that become particularly acute during compound extremes when multiple drivers interact to amplify coastal impacts. These limitations motivate the present work, which aims to advance understanding and predictive capability in coastal–ocean systems through a multi-process, integrated numerical modelling. The following sections examine the extreme drivers of coastal dynamics, emphasizing how coupled, forced, and cross-scale numerical approaches are essential to capture the full complexity of coastal hazards and enhance model realism.

1.2 Storm surge, wave extremes and coastal erosion

Coastal zones are especially vulnerable both to acute and chronic hazards related to climate variability and change, with an immediate impacts from extreme sea level events (Von Storch and Woth, 2008). The main threats are rising sea levels, extreme waves, and storm surges, which can cause land loss, coastal erosion, inundation, and changes in the physical-chemical properties of seawater, which can affect biodiversity and ecosystem services in coastal waters (Edenhofer et al. (2014)). Climate change has already caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater, cryospheric and coastal and open ocean ecosystems. Cid et al. (2016) found positive trends in the duration of storm surges in certain Mediterranean

areas, with increasing rates of $0.5 - 1.5 \text{ h/year}$, and large spatial variability with relative higher values along the coasts. They have also found negative correlation with the NAO (North Atlantic Oscillation) index to increase the number of extreme events. Camelo et al. (2020) investigated the impacts of hurricane-induced storm surges in the Gulf of Mexico and Atlantic Coast and found increased volumes of inundations with the average positive change of 13%, with higher projections by the end of the century.

The extent and magnitude of climate change impacts are larger than estimated in previous assessments, it exacerbated land degradation, particularly in low lying coastal areas, river deltas, drylands, according to IPCC report (Lee et al. (2023)), where 50% of coastal wetlands have been lost over the last 100 years, as a result of the combined effects of localised anthropogenic and natural causes. Rising sea levels from climate change and associated storm surge may also pose a significant risk for relatively vulnerable components of the electricity system (Enriken and Lordan (2012)). Sea level rise will cause losses of coastal ecosystems and their services, flooding and damages to coastal infrastructure, permanent submergence of areas, increased coastal erosion and chronic long-term erosion, wetland change and loss, salinity intrusion into coastal aquifers and the lower reaches of rivers (Wong et al. (2014)). Global land loss can amount up to $17,000 \text{ km}^2$ during the 21st century, leading to 1.6 - 5.3 million people being forced to migrate (Hinkel et al. (2013)).

Gravity waves are often primary drivers of coastal flooding and erosion over various time scales, however the extreme wave height estimates are typically characterized by large statistical uncertainty. Long-term satellite datasets analysis by Young and Ribal (2019) have shown that wind-wave climate is changing with the positive trends in Southern Oceans by up to 15%, and at high latitudes over North Atlantic and North Pacific by 5 to 10% in 21st century (Meucci et al. (2020)). Based on CMIP (Coupled Model Intercomparison Project) the GCM-forced (Global Climate Model) wind-wave simulations (Morim et al. (2019)) demonstrate robust changes in annual mean significant wave height and mean wave period of similar ranges (5 - 15%), with

shifting wave directions of 5-15°. These studies show the projected changes exhibit strong inter-hemispheric asymmetry, with the decreases in low to mid latitudes of Northern Hemisphere up to 15% (Meucci et al., 2020; Morim et al., 2021). Wind-wave extremes are crucial for the determination of coastal sea levels and coastal erosion, and changes in the climate may further exacerbate the already predicted strong societal and economic impacts. Luijendijk et al. (2018) analysis of the satellite derived shoreline data indicates that 24% of the world's sandy beaches are eroding at rates exceeding 0.5 m/year, while 28% are accreting.

1.3 Multi-model integration for coastal-ocean dynamics

These compounded pressures, together with the strong spatial–temporal heterogeneity of forcing and response, necessitate an advanced integrated modelling approach. Therefore current work adopts a multi-model, cross-scale approach in which complementary numerical cores, such as circulation, spectral waves, and sediment/morphodynamics are combined to resolve air–sea momentum and heat fluxes under evolving sea state, capture two-way wave–current interactions driving surge and total water level (TWL), represent wave- and current-driven bed shear stresses controlling resuspension and morphology, and accommodate strong resolution gradients from open sea to the nearshore, leveraging the unstructured grid capabilities of the models. Figure 1.3.1 illustrates the multi-model integration used in this work, indicating the interactions between different model components through the exchange of scalar and vector terms. In the following sections, we motivate and provide objectives for each constituent component of this framework, by constructing the core coupled hydrodynamics (Section 1.3.1), followed by the benthic boundary layer integration into the wave model (Section 1.3.2), and sediments-driven morphodynamics (Section 1.3.3). Then the corresponding chapters will dive into the details of the model implementation, experiments, and applications.

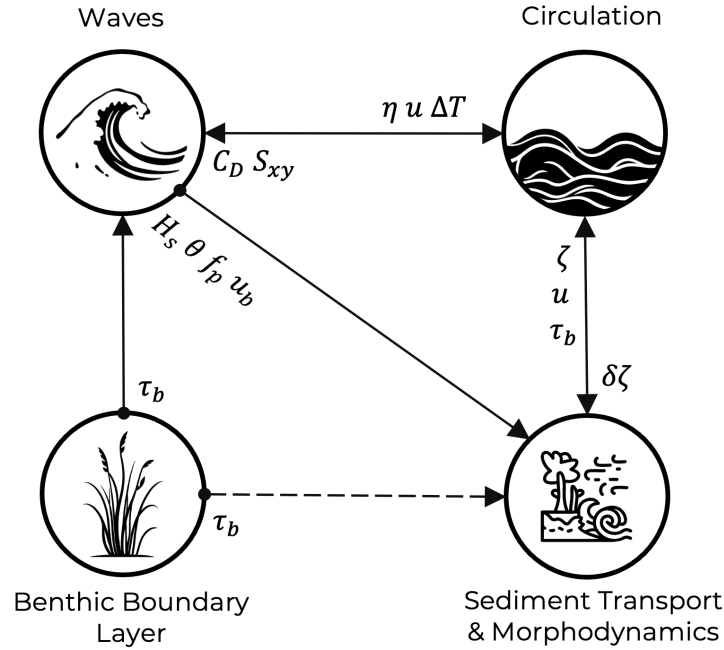


Figure 1.3.1. Schematic representation of the multi-model integration framework. The arrows indicate the exchange of scalar and vector terms between different model components. The dashed arrow indicates the yet unestablished interaction, that is not considered in this work. η is the sea surface elevation, τ_b is the bottom friction, $\mathbf{u}$ is the current velocity, H_s is the significant wave height, f_p is the peak frequency, θ is the wave direction, $\mathbf{u}_b$ is the near-bed wave orbital velocity, ζ is the bed elevation, $\delta\zeta$ is the bed level change, ΔT is the air-sea temperature difference, $\mathbf{S}_{xy}$ is the radiation stress tensor (S_{xx}, S_{xy}, S_{yy}), and C_D is the neutral drag coefficient.

1.3.1 Waves and circulation

Ocean waves and currents interaction is of great importance for various applications (Li et al., 2014; Zambon et al., 2014), including weather forecasting for sea surface temperature (SST) predictions (Takaya et al. (2010)), as wave-induced mixing can strongly influence upper-ocean stratification and heat exchange (Aijaz et al. (2017)), leading to significant cooling and deepening of the mixed layer. In coastal zones, waves play a crucial role in modulating water levels and driving littoral processes (Longuet-Higgins and Stewart (1962)), particularly through the gener-

ation of longshore currents and cross-shore transports that shape sediment dynamics and shoreline morphology (Bühler and Jacobson, 2001; Longuet-Higgins, 1970). The coupling objectives within the scope of this work is to investigate the effects of a two-way coupled wave-circulation modelling during extreme weather events, with a particular focus on the Mediterranean tropical-like cyclones, also known as Medicanes (Cavicchia et al. (2014)). These are extreme cyclonic windstorms with a frequency of one to two events per year evolving over the Mediterranean Sea and posing a serious threat to the densely populated coastal areas (Romero and Emanuel (2013)). By utilizing a high-resolution unstructured numerical grid shared between the wave and circulation models, we explore wave-current interactions in both open ocean and the coastal environment in Chapter 2 (Causio et al. (2025)). This defines the core wave-current interaction layer that underpins subsequent extension to sediment transport and morphodynamics through wave- and current-enhanced bed shear, resuspension, and consequent bed evolution.

1.3.2 Benthic boundary layer

Benthic boundary layer is the layer of the water column, directly above the seabed, where the flow is influenced by the presence of benthic habitats, such as seagrasses, kelp and coral reefs, acting as significant roughness elements. These habitats modify the velocity profiles (Beth Schaefer and Nepf (2022)), increase turbulence, creating eddies and swirls, and exert drag forces altering the transport of nutrients and sediments (Reidenbach et al., 2006; Monismith et al., 2019). Marine habitats are of great importance to the coastal environment providing many services, such as shoreline stabilization via wave energy attenuation and bed shear stress reduction (Paul et al., 2012); sediment trapping, consolidation and decreased resuspension (Gacia and Duarte, 2001); blue-carbon sequestration with long-term burial of organic carbon in matte/sediments (Johannessen, 2023; Bulmer et al., 2024); nursery, spawning and refuge habitat enhancing biodiversity and fisheries productivity; nutrient cycling and transformation, through uptake, remineralization, and denitrification facilitation (Wang et al., 2020); water quality improvement

via particulate interception and oxygen release (Paynter, 2024; Roca et al., 2015); natural coastal defense mitigating (Sánchez-González et al., 2011; Infantes et al., 2012). Among the dominant physical disturbances degrading these vegetated canopies are high-energy storm events, whose intensified orbital velocities and episodic shear can induce blade breakage, canopy thinning, localized scour, and rhizome exposure (Oprandi et al., 2020b). Conversely, continuous and structurally complex seagrass meadows attenuate incident wave energy through form drag, blade reconfiguration and induced turbulence, preferential damping of short (high-frequency) components, and consequent reductions in significant wave height, steepness, and near-bed shear stress (Beudin et al., 2017; Vettori et al., 2025).

These contrasting roles of benthic canopies, as both dissipators and responders to hydrodynamic forcing, demand that their influence on wave propagation and near-bed stress be explicitly represented in the coastal models. To address this, we quantify the one-way biomechanical effect of the *P. oceanica* meadows on wave transformation in the Balearic Islands by applying a flexibility term within the bottom dissipation of the spectral wave model. Decadal seasonal observations are integrated to represent seagrass phenological cycles, and the resulting variability of wave attenuation along the Civitavecchia coastline is evaluated in Chapter 3.

1.3.3 Sediment transport and morphodynamics

Shallow deltaic and estuarine margins experience tightly coupled wave, current, tidal, and river forcing, which necessitate tools capable of accounting for the interactions between the main factors that drive sediment transport, shoreline and seabed evolution patterns (Seminara, 2001; Pye and Blott, 2006). Process control resides in the bottom boundary layer: oscillatory wave orbital motion superimposed on mean current shear sets the instantaneous distribution of bed stresses, defines bedform regime through the form drag, and dictates thresholds for initiation of motion, deposition and re-suspension (Grant and Madsen, 1979; Myrhaug, 1995; Soulsby, 1997; Julien, 2010; Van Rijn, 1993). When combined, waves and currents control the rout-

ing of suspended and bedload sediments, particularly in the surf zone (Bowen, 1969; Franz et al., 2017). Ignoring coastal erosion patterns may lead to underestimation of flood hazards, as morphodynamic adjustments can amplify flooding by up to 15%, and more in case of extreme events (Cueto et al., 2022). Many established sediment transport and morphodynamics (STM) models rely on domain-limited idealized geometries, parameterized wave forcing, uniform flow regime - bedload transport formulations, lack feedbacks between evolving bathymetry and hydrodynamics, and are opted for specific purposes as detailed in Hoagland et al. (2023). A major challenge in developing a generic and comprehensive model is the scarcity of observational datasets and robust validation methodologies (Bosboom et al., 2020). Such validation would require high-resolution bathymetric surveys resolving local bed slopes that govern particle rolling and sliding, together with sustained time series of suspended and near-bed sediment concentrations (SSC) in the water column. Consequently, the development of STM models often relies on idealized domains benchmarked against laboratory experiments before application to real-world settings, a process that necessitates accounting for a wide range of interacting flow regimes and forcing conditions. Foundational experimental and theoretical studies (e.g., Lanzoni and Seminara, 2002; Tambroni et al., 2005, 2010) provide critical insight into the morphodynamics of tidal inlets and channels under controlled conditions. Although their focus on idealized, tidally dominated systems differs from the event-driven, wave–current coupled configuration examined here, they represent valuable benchmark cases for future validation of long-term inlet evolution and sediment–vegetation interactions (D’Alpaos et al., 2007), and the environments governed by these systems (Tambroni and Seminara, 2006).

Building on the earlier SHYFEM-based sediment transport module (Ferrarin et al., 2008), we introduce several key enhancements to better capture the coupled dynamics of waves, currents, and seabed evolution. The updated formulation incorporates offline spectral wave forcing from the coupled core (Section 1.3.1), applies unified wave–current shear and bedform roughness parameterizations for ripples, megaripples, and dunes based on Van Rijn (2007), and em-

employs intra-wave bedload transport to resolve short-term variability in bottom stresses. We compute suspended-load profiles with a Rouse distribution and evaluate the vertical integral using composite Simpson’s rule to better resolve near-bed concentrations. The model further distinguishes between imposed initial seabed morphology and time-varying riverine sediment supply, while feeding Exner-based bed evolution back into the hydrodynamics via the free surface equation, ensuring that bathymetric changes instantaneously influence currents and stresses. Riverine morphodynamic feedbacks are also represented through secondary-current effects, as well as slope and angle corrections to the bedload transport vector. This extended STM model is implemented within the SHYFEM-MPI (Micaletto et al., 2022), sharing time-stepping and the unstructured grid with the circulation and wave cores. The wave-aware, enhanced three-dimensional STM model is first tested on idealized configurations of a tidal inlet and a river meander reach to benchmark bed evolution and hydrodynamics against reference models in Chapter 4. It is subsequently applied at the complex coast off the Tiber River mouth (Lazio coast) to assess long-term performance using in-situ measurements and satellite-derived suspended particulate matter.

1.4 Thesis objectives

Following the detailed exposition of the scientific context and methodological developments in the preceding sections, the ensuing synthesis encapsulates the central aims of this study. The primary objective of this thesis is to develop, validate, and apply an integrated, multi-model numerical framework to advance the understanding and prediction of complex coastal–ocean dynamics, consistent with the *United Nations Decade of Ocean Science for Sustainable Development (2021–2030)* (Ryabinin et al., 2019), which calls for transformative ocean science to reverse the decline in ocean health and to catalyse equitable use of marine resources. In line with the UN Decade’s goals this work contributes to the development of a coherent, observation-

informed modelling framework. The approach integrates multiple physical processes to improve predictability of coastal–ocean responses to natural and anthropogenic pressures. Specifically, this overarching aim is subdivided into the following research constituents:

1. Establishment of a dynamically consistent two-way coupling on a shared unstructured grid to quantify mutual interactions between wave and circulation fields, including sea-state dependent momentum flux, radiation stress, Doppler shift, dynamic water depth for waves, and effective wind speed. The coupled system is applied to Mediterranean tropical-like cyclones (Medicanes) to assess effects on storm surge, total water level, and upper-ocean stratification (Chapter 2).
2. Representation of the biomechanical influence of *Posidonia oceanica* meadows on wave transformation by incorporating flexible canopy-induced bottom dissipation within the spectral wave model. Seasonal variability in wave characteristics is assessed through the synergistic integration of long-term observational data within the numerical model, to evaluate the role of vegetated beds in attenuating wave energy along the Civitavecchia and Balearic coasts (Chapter 3).
3. Extension of the SHYFEM-MPI sediment module to incorporate unified wave–current shear and bedform roughness parameterizations, intra-wave bedload transport, and dynamic feedback of bed evolution on hydrodynamics. The model is first validated against idealized benchmarks and then applied to the Lazio coast, along the Fiumicino coastal zone, to examine coupled morphodynamic responses under realistic wave, current, and riverine forcing (Chapter 4).

Together, these objectives establish a unified modelling strategy that links hydrodynamic, benthic, and morphodynamic processes, enhancing realism and robustness in simulations of coastal extremes. The thesis is structured to reflect this progression, systematically presenting

the development, validation, and application of each component within the unified modelling framework. Chapter 5 synthesizes the principal findings and presents the conclusions.

Chapter 2

Coupling ocean currents and waves for seamless cross-scale modelling

This section is dedicated to the publication of the Causio et al. (2025) study in the journal of Ocean Science. It describes the development of the two-way coupling between SHYFEM-MPI and WW3 numerical models, with the objective of studying the Medicane Ianos and the analysis of the impact on wave- and circulation models through the exchange of the scalar and vector terms. It aims to develop the core coupled interface as illustrated in Figure 2.0.1.

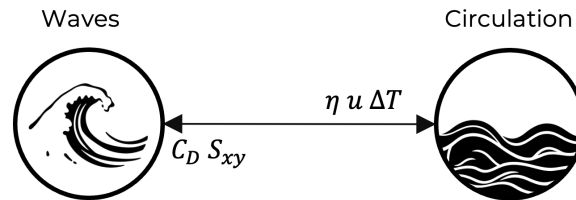


Figure 2.0.1. Schematic representation of the two-way coupling between SHYFEM-MPI and WW3 models. It represents the core wave-current interaction layer that builds the foundation for the multi-model integration framework (Figure 1.3.1).

2.1 Physics of coupled systems and the scope

Advanced knowledge on surface wind-driven gravity waves and currents, and their interactions in the ocean is of great relevance to many decision support systems, such as meteocean forecast-

ing, early warning for storm surge events, oil spill evolution, search and rescue, beach erosion, site choices for offshore infrastructure (Hashemi and Neill (2014)). Physically, the surface gravity waves can affect the vertical mixing, as well as surface and bottom stresses experienced by currents. Surface waves and currents can also exchange energy through the concept of radiation stress (Longuet-Higgins and Stewart (1961); Mellor (2003)) or vortex force (VF) (Ardhuin et al. (2008); McWilliams et al. (2004)). In return, ocean currents can modify the relative speed of the air above the sea surface (relative wind effect) and change the absolute frequency of waves due to the Doppler shift. Spatial variability of currents can modify the relative wave frequency and cause wave refraction, shoaling, and breaking that mimic bathymetric effects.

2.1.1 Storm-induced coastal hazards and Mediterranean cyclones

An accurate computation of the total water level (TWL) during storm surge events combining multiple drivers (e.g. surges, tides, waves) becomes relevant to forecast flooding and impacts in coastal and urban areas. Kim et al. (2008) used a coupled surge-wave-tide (SuWAT) model to demonstrate that high tides can mitigate storm surges. Their study highlighted the relationship between locally generated surge and wave setup with the tidal state. They emphasized that considering surges, waves, and tides independently can lead to an overestimation of TWL. Additionally, they underscored the importance of incorporating bottom friction, wind-wave interactions, and wave-current interactions for more accurate storm surge estimations. Continuing the development, with the focus on the effects of wind stress parameterizations and wave-induced radiation stress on storm surge, Kim et al. (2010) estimated 40% contribution of radiation stresses to the peak sea level rise.

Jo et al. (2024) studied the typhoon-caused inundations concluding that uncoupled models overestimate wave-overtopping peak discharge by 8%. Hsiao et al. (2019) used fully coupled circulation-wave model (SCHISM + WW3) to simulate super typhoon events. They observed that surface waves, especially wave setups exhibited the most significant nonlinear interaction

with storm tides, while wave-tide interaction was relatively minor. Dietrich et al. (2011) coupled a shallow-water model (ADCIRC) with the wave model SWAN, utilizing the same unstructured grid to simulate the waves and storm surges induced by the hurricanes Katrina and Rita in the Gulf of Mexico. The model demonstrated that as the hurricane Katrina moved onto the continental shelf, depth-limited breaking waves exerted stresses on the water column, increasing overall water levels by 0.2–0.3 m and driving currents, contributing up to 35% of the TWL and 10% of overall currents in the region.

Extreme meteorological events are intensifying in the Mediterranean Sea due to climate changes, among these we have the Mediterranean tropical-like cyclones or Medicanes (Cavicchia et al. (2014); Sánchez-Arcilla et al. (2016)). Medicanes are rare meteorological phenomena that exhibit characteristics similar to tropical cyclones, such as a warm core, eye formation, and strong winds. These systems, however, form and evolve under the unique conditions of the Mediterranean Sea, typically during the autumn and early winter months when sea surface temperatures are sufficiently warm to support their development (Cavicchia et al. (2014)). Although Medicanes are generally less intense and shorter-lived compared to their tropical counterparts, they can still cause significant damage and pose considerable risks to the regions they affect. Notable examples include Medicane Rolf in 2011 and Medicane Zorbas in 2018, both of which provided valuable insights into the dynamics and impacts of these systems (Flaounas et al. (2022)).

2.1.2 Medicane Ianos and the objectives

Among the most harmful recent Medicanes is Medicane Ianos, which struck Greece in September 2020, causing widespread damages, exceeding 700 millions of dollars and resulting in human casualties (Diakakis et al. (2023)). The study of Medicanes is crucial for advancing our understanding of these phenomena and enhancing preparedness and response strategies in the Mediterranean region (Ferrarin et al. (2023)).

This study aims to investigate the impact of a two-way coupled wave-circulation model on ocean dynamics during extreme events, with a focus on Mediane Ianos. Using very high-resolution and unstructured numerical grid, we describe the contribution of wave-currents interaction during one of the most intense cyclones in the Mediterranean Sea. We carried out this work using a new modelling framework based on SHYFEM-MPI (Micaletto et al. (2022); Verri et al. (2023)) and a state-of-the-art community wave model WAVEWATCH III (hereafter WW3) (Tolman et al. (2009); WW3DG). For this study, an external Python-based coupler is developed to manage the mutual exchanges between the numerical cores, enabling two-way coupling. The WW3 model is widely used by several organizations worldwide to simulate waves in various systems across different regions, ranging from global (Alday et al. (2021); Brus et al. (2021); Mentaschi et al. (2020)) to regional (Abdolali et al. (2020); Causio et al. (2021); Causio et al. (2024)) and coastal scales (Pillai et al. (2022b); Pillai et al. (2022a)).

The SHYFEM model has previously been coupled with wave models, as in Roland et al. (2009). It serves as the circulation core of the storm surge early warning system Kassandra (Ferrarin et al. (2013)) and has recently been employed to analyze uncertainties related to the simulation of the Mediane Ianos (Ferrarin et al. (2023)). In these studies, they adopted a barotropic implementation, with the unstructured WWMIII wave model (Roland et al. (2009)) integrated through hard-coupling.

Present work incorporates new processes into the two-way coupling between SHYFEM-WW3, including the sea state dependent momentum flux and wind field correction based on the air stability parameter. The study marks the first study to implement a three-dimensional baroclinic version of wave coupled SHYFEM model.

The reliability of the results and the code are validated using well-established idealized benchmarks and analytical results. Specifically, we use the planar beach (Xia et al. (2020)) and the wave-tidal-driven inlet (Cobb and Blain (2002)). Furthermore, this newly developed coupled system is applied to a real-case, simulating the impacts of Mediane Ianos on ocean

and wave fields, as well as their interactions, using a cross-scale unstructured-grid domain. This domain enables us to examine both (i) open ocean features, such as sea surface cooling induced by the Medicane, the impact of the coupling on vertical profiles, and the effects of circulation on large scale wave dynamics, and (ii) local coastal features, including TWL and wave contribution to storm surge.

The work is structured as follows. Section 2.2 introduces the modelling framework, including the circulation and wave modelling suite as well as the coupling methodology. Section 2.3 validates the coupling procedure using idealized test cases. Section 2.4 investigates the Medicane induced effects on the ocean, with a specific focus on coastal storm surge. Finally, the results are presented in Section 2.4.2, followed by the discussion in Section 2.5.

2.2 The modelling framework

This study is based on a coupled modelling framework built on WW3 and SHYFEM-MPI. Both models run on the same unstructured computational grid, a classic methodology in coupled unstructured modelling, used from early studies to the most recent ones, such as in (Mentaschi et al. (2023)). This avoids further interpolations, and it allows a seamless approach to address large-scale and coastal processes. Unstructured grids also ensure an accurate representation of both natural and artificial irregular coastal features (Bertin et al. (2014)), and it allows for high-resolution modelling along the coast.

2.2.1 Circulation modelling

The circulation model used in this study is SHYFEM (System of Hydrodynamic Finite Element Module), a 3D baroclinic finite-element hydrodynamic model (Umgiesser et al. (2004); Federico et al. (2017); Verri et al. (2023)) that solves the Navier–Stokes equations by applying the hydrostatic and Boussinesq approximations. The SHYFEM-MPI version, developed by the

Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) Micaletto et al. (2022), is used in this study and, for the first time, is coupled with the wave model WW3.

The model employs a semi-implicit algorithm for time integration, providing unconditional stability with respect to gravity waves, bottom friction, and Coriolis terms, thus allowing transport variables to be solved explicitly. The Coriolis term and pressure gradient in the momentum equation, along with the divergence terms in the continuity equation, are treated semi-implicitly. Bottom friction and vertical eddy viscosity are treated fully implicitly for stability reasons, while the remaining terms (advective and horizontal diffusion terms in the momentum equation) are treated explicitly. The finite element discretization is applied on unstructured B-type grids. More detailed descriptions of the model equations and discretization methods are provided in Micaletto et al. (2022) and Verri et al. (2023).

A select group of circulation models utilize the finite element method (FEM) on unstructured domains, including TELEMAC-3D (Moulinec et al., 2011), SELFE (Zhang and Baptista, 2008), which evolved into the semi-implicit, cross-scale SCHISM (Zhang et al., 2016), the large- to global-climate-scale ocean-sea ice model FESOM (Wang et al., 2014), as well as the coastal model Thetis (Kärnä et al., 2018), implemented via the FEM solver - Firedrake platform (Rathgeber et al., 2016), leveraging high-level abstractions to define the weak formulation of the governing partial differential equations.

These models have been successfully applied to predicting complex tidal dynamics (Eric Jones and Davies, 2006) and high-resolution storm surges through coupled wave-circulation modeling (Bertin et al., 2015). Their primary advantage lies in superior geometric flexibility, given by unstructured discretization (Chen et al., 2003), which allows for the precise representation of coastlines and steep bathymetric gradients without grid-stepping artifacts, even facilitating the implementation of advanced adaptive meshing mechanisms (Danilov, 2013; Piggott et al., 2008). In addition, the FEM formulation is based on a variational form of the governing equations, enabling consistent treatment of irregular boundaries and supporting higher-

order spatial approximation and local mesh refinement within a unified mathematical framework making it attractive for ocean circulation modelling (Fix, 1975). FEM formulations have demonstrated superior accuracy and stability compared to those obtained with traditional finite-difference methods (Dumas et al., 1982).

Despite these benefits, FEM-based models typically entail higher computational overhead compared to finite-difference models. They also face numerical challenges, such as the requirement for stabilization in advection-dominated flows (Wang et al., 2008), and often necessitate solving a fully coupled global system, which can limit parallel efficiency compared to finite volume (FV) methods (Danilov, 2012).

Therefore, by utilizing a staggered mixed-finite-element discretization and a semi-implicit time-stepping scheme, the numerically stable SHYFEM-MPI emerges as a suitable candidate for wave-circulation coupling and the establishment of morphodynamic modules. This framework allows mesoscale dynamics to be finely resolved in coastal areas while maintaining computational tractability in the open ocean. Besides, the model has been successfully applied in operational (Federico et al. (2017)) and relocatable forecasting systems (Trotta et al. (2021)), storm surge events (Alessandri et al. (2023); Park et al. (2022)), and as a part of a digital twin (Pillai et al. (2022b)).

In this work, we implemented the transport and diffusion equation for tracers, with horizontal and vertical advection values based on a total variation diminishing (TVD) scheme. An upwind scheme is employed to discretize the horizontal advection of momentum, and the Smagorinsky (1963) formulation is used to compute horizontal eddy viscosity. Vertical viscosities and diffusivities are calculated using a $k - \epsilon$ scheme adapted from the General Ocean Turbulence Model (GOTM) (Burchard and Petersen (1999b)). Bottom stress is computed using the quadratic formulation with a bottom drag coefficient defined based on the logarithmic formulation and water depth. In the logarithmic formulation, the von Karman constant is assigned a value of 0.4, and the bottom roughness length is 0.01.

2.2.2 Wave modelling

The wave model used is WW3 v6.07, a third-generation wave modelling framework that incorporates the latest scientific advancements in wind-wave modelling and dynamics. Developed by the US National Centers for Environmental Prediction (NOAA/NCEP) and inspired by the WAM model (Komen et al. (1984)), WW3 solves the random phase spectral action density balance equation for wavenumber-direction spectra. The model includes options for shallow-water (surf zone) applications and features numerical schemes capable of solving the propagation of a wave spectrum at high resolutions on unstructured (triangular) grids (Abdolali et al. (2020)).

In this study, the wave energy spectra are discretized into 24 equally spaced directional bins covering the full circle, and a 30 log-varying frequency discretization (0.05–0.7932 Hz). The source input and dissipation terms are based on the Source Term 4 (ST4, package T741) physics from Ardhuin et al. (2010). Non-linear wave-wave interactions are implemented using the Discrete Interaction Approximation (DIA) from (Hasselmann et al. (1985)). Bottom friction is defined using the JONSWAP parametrization (Hasselmann et al. (1973)), and depth-induced breaking follows the criterion described by Battjes and Janssen (1978) and Miche (1944) for defining the breaking threshold. Furthermore, we calibrated the wind-wave coupling parameter (BETAMAX=1.43) to improve model results and reduce the underestimation of wave height. Nonlinear triad interactions are modeled using the Lumped Triad Approximation (LTA) model of Eldeberky and Battjes (1996). Second-order propagation scheme Contour Residual Distribution – Positive Streamline Invariant (CRD-PSI) (Roland et al. (2009)) is used to describe wave propagation with a global timestep of 200s.

2.2.3 Coupling methodology

The two-way interaction in the modelling framework is achieved via an external Python-based coupler, which has the advantage of using the native versions of the standalone models, thereby

minimizing code changes. The primary changes applied to the native codes relates to new physical processes inclusion. For this study, multiple sensitivity tests are conducted to evaluate the system's response to the coupling frequency ($\Delta t_{coupling}$), identifying 1 hour as an optimal balance between the exchange frequency and the computational performance. However, $\Delta t_{coupling}$ is set to 30 minutes for the idealized test cases to be consistent with previous studies, while 1 hour is used for the real case.

The main objective of this study is to characterize the wave-induced surge component in the total water level, with a focus on the effect of waves on circulation. This involves incorporating the theory of Longuet-Higgins and Stewart (1961). Additionally, to provide a more comprehensive set of interactions from coastal to large scale, we include sea-state-dependent momentum flux, based on the neutral drag coefficient, as described by Clementi et al. (2017). Conversely, to preserve the integrity of two-way interactions, the effect of circulation on waves is addressed by incorporating the Doppler shift induced by surface ocean currents, by dynamically updating the water depth based on the sea-surface height and by correcting the wind field according to a stability parameter dependent on the air-sea temperature difference (Abdalla and Bidlot (2002)). This approach accounts for wind gustiness, which can enhance the representation of extreme conditions during storms (Abdalla and Cavaleri (2002)).

A schematic representation of the two-way coupling is shown in Figure 2.2.1 and detailed below. The circulation model receives the radiation stress components and the wind neutral drag coefficient computed by the wave model. The radiation stress components S_{xx} , S_{xy} and S_{yy} account for wave transformation in coastal areas, resulting in a net flux of momentum. According to the Longuet-Higgins and Stewart (1964) theory, wave setup balances the shoreward gradient in radiation stress, with the sea surface pressure gradient counteracting the gradient of incoming momentum. The wave-induced momentum flux (F), derived by the gradients of the radiation stress is estimated and included in the momentum equation (Eq. 2.2.1).

$$F = \frac{1}{\rho} \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}, \frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) \quad (2.2.1)$$

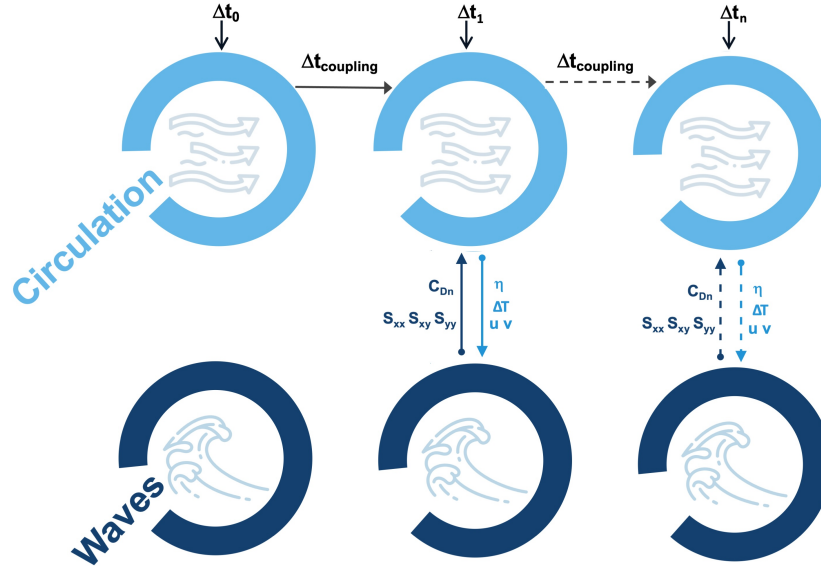


Figure 2.2.1. The coupling procedure between SHYFEM-MPI and WW3. When the simulation starts, models exchange information after the first time step (e.g. $\Delta t_0 = 300s$), then exchange every $\Delta t_{coupling}$ (e.g. every 1h). SHYFEM-MPI sends sea level (η), current fields (u, v) and air-sea temperature difference (ΔT) to WW3. WW3 sends neutral drag coefficient (C_{Dn}) and radiation stresses (S_{xx}, S_{xy}, S_{yy}) to SHYFEM-MPI.

The sea-state dependent wind stress involves exchanging the neutral drag coefficient from the WW3 wave model, following Clementi et al. (2017). This coefficient is computed using a formulation derived from the quasi-linear theory of wind-wave generation, as developed by Janssen (1989), Janssen (1991) and based on Miles (1957). According to this theory, the neutral drag coefficient (C_{Dn}) (Eq. 2.2.2) depends on the effective roughness length, which is influenced by the sea state through the wave-induced stress estimated from the wave spectra.

$$C_{Dn} = \left(\frac{\kappa}{\log\left(\frac{z_u}{z_0}\right)} \right)^2 \quad (2.2.2)$$

Where z_u is the height of the wind forcing, $\kappa = 0.4$ is the von Karman constant, and z_0 is the roughness length modified by the ratio of the wave-supported stress τ_w to the total stress τ , as

in Eq. 2.2.3. τ_w represents the flux of momentum that is directly input into the wave field by the wind.

$$z_0 = \frac{\alpha_0 \tau}{\sqrt{1 - \tau_w / \tau}} \quad (2.2.3)$$

Where $\alpha_0 = 0.0095$. The C_{D_n} is transferred to the circulation model for the estimation of the turbulent drag coefficient according to Large (2006). The circulation interacts with the wave field through sea level, currents, and air-sea temperature difference. The sea level (η) allows for a dynamic adjustment (d) of the water depth (h) in the wave equations as in Eq. 2.2.4:

$$d = h + \eta \quad (2.2.4)$$

Ocean currents influence wave characteristics, including wavelength, amplitude, wavenumber, and direction. In the WW3 model, the Doppler shift accounts for the changes in wave frequency due to the relative motion between waves and currents, which can be expressed as in Eq. 2.2.5:

$$\omega = \sigma + \mathbf{k} \cdot \mathbf{U} \quad (2.2.5)$$

ω : absolute frequency, σ : relative frequency, $\mathbf{k}$: vector of wave number, $\mathbf{U}$: current velocity.

The stability of the atmosphere is influenced by the air-sea temperature difference (ΔT). Tolman (2002), inspired by the work of Abdalla and Bidlot (2002), formulated a stability correction replacing the wind speed in WW3 with an effective wind speed, ensuring that the wave growth correspond to both stable and unstable wave growth patterns. The ΔT defines a stability parameter according to Eq. 2.2.6:

$$ST = \frac{hg}{U_z^2} \frac{\Delta T}{T_0} \quad (2.2.6)$$

U_z : wind speed at height z , ΔT : air-sea temperature difference, T_0 : reference temperature. ST is used to compute effective wind speed, U_e (Eq. 2.2.7):

$$U_e = U_{10} \left(\frac{c_0}{1 \pm c_1 \tanh[c_2(ST - ST_0)]} \right)^{\frac{1}{2}} \quad (2.2.7)$$

U_{10} : wind speed at 10m, c_0 : 1.4, c_1 : 0.1, c_2 : 150, and ST_0 : -0.0.1.

2.3 Validation of the coupled model

The robustness of the two-way coupling and its physics is assessed and evaluated through idealized numerical experiments. The test cases selected for this assessment include two common benchmarks for the wave-currents interaction at coastal scale: a planar beach (Figure 2.3.1(a)) from Xia et al. (2020) and an idealized tidal inlet (Figure 2.3.1(b)) from Cobb and Blain (2002).

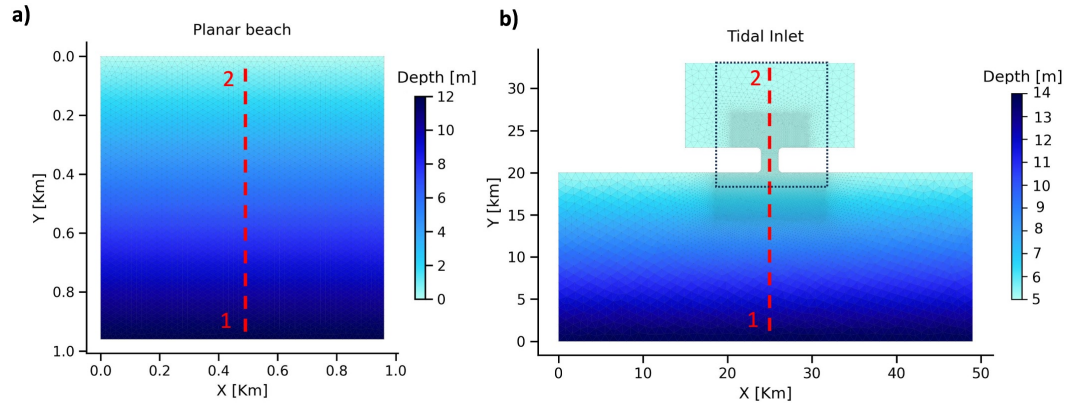


Figure 2.3.1. Numerical domain and bathymetry of the two idealized benchmarks: the planar beach (a) and the tidal inlet (b). Dashed red lines show the transect from point 1 to point 2, where the numerical solutions were assessed. The dotted box in (b) denotes the area magnified and is shown later in the 2.3.3.

Table 2.3.1 lists the acronyms of the simulations used for the validation of the idealized testcases.

2.3.1 Planar beach

The planar beach is used in this work for assessing the wave setup/setdown along the transect 1-2 (Figure 2.3.1(a)). The results obtained from our numerical model are compared with the

Table 2.3.1. Configurations and nomenclature for the numerical setup used in this study.

Abbreviation	Description
W-O	Standalone wave model
C-O	Standalone circulation model
W-C	Two-way coupled system wave–circulation
C-WF	Circulation model forced by wave

analytical solution as described in Xia et al. (2004), to validate the accuracy and reliability of the implementation in modelling wave contributions to the surge, ensuring that the modeled outcomes are consistent with the theoretical solution. The validation is carried out utilizing the C-WF configuration, where the wave model exclusively provides inputs (forcing fields) to the circulation model. This setup allows the model to reach a semi-stationary condition more quickly.

The planar beach is a gently sloping square basin with a side length of 960 m, as illustrated in Figure 2.3.1(a). The bathymetry is constant along the shore and slopes linearly from 0 to 12 m in the cross-shore direction. The numerical grid has 5400 elements and 2797 nodes, and a horizontal resolution of approximately 20 m. The vertical discretization consists of 12 z-levels, each with a thickness of 1 m. The wave model is forced along the open boundary by waves with a 2 m significant wave height (SWH), a peak period of 10 seconds, and a 10-degrees oblique angle relative to the shore-normal direction, using a JONSWAP spectral shape. The circulation model starts from a resting state and is only influenced by the radiation stress from the WW3 model, with no other external forcings applied. These simulation conditions derive from Xia et al. (2020)

As the waves propagated from the offshore open boundary within the model domain, they start to shoal and breaking approximately 600 m from the shore, at which point the depth-induced breaking criterion is met. As shown in Figure 2.3.2, the simulated surface elevation

produced by the circulation model match properly with the analytical solution (Wang and Sheng (2016); Xia et al. (2004)).

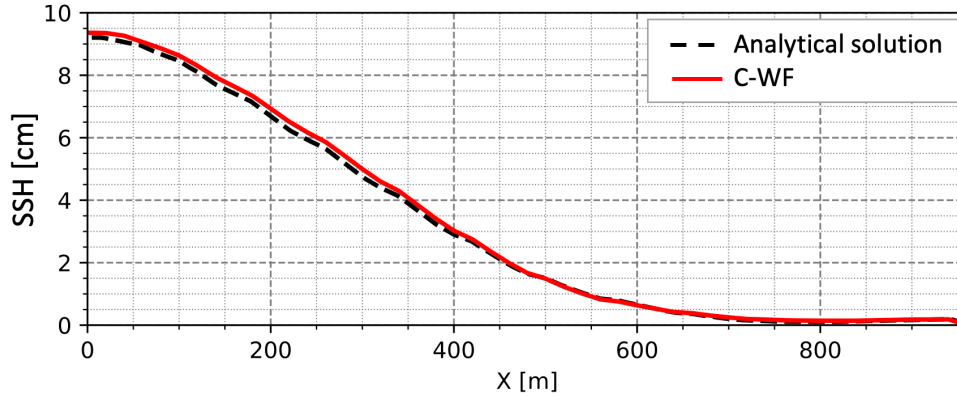


Figure 2.3.2. Planar beach testcase: comparison between model and analytical solution along the transect 1-2 shown in Figure 2.3.1(a). The testcase verifies the C-WF simulation, assessing the role of wave set-up (via radiation stresses) to the total water level.

2.3.2 The coastal inlet

A second benchmark defined as coastal inlet, is used in this study to conduct a series of simulations that highlight the interactions between waves and sea level. These simulations enable the assessment of wave-induced circulation, the impact of currents on wave dynamics, and the mutual interactions between waves and currents. We conducted several simulations using the following configurations: W-0, an uncoupled wave model simulation; C-0, an uncoupled circulation model simulation; C-WF, where the wave model exclusively supplies fields to the circulation model; and W-C, the two-way coupled configuration. The outcomes of our simulations are then compared with those reported in the existing literature, as cited in the discussion of the results.

The tidal inlet (Figure 2.3.1(b)) used in this study derives from the work of Cobb and Blain (2002), based on Kapolnai et al. (1996). The domain recreates an inner basin (lagoon or embayment) measuring 20 km by 10 km, linked to an outer ocean basin of 49 km by 20 km on the continental shelf via a narrow 3 km long and 2 km wide channel. The bathymetry shows a linear slope from a depth of 14 m offshore to 5 m at the channel's entrance, with a consistent depth of 5 m beyond the channel. The unstructured grid resolution is approximately 125 m within the channel and the surrounding area and 1 kilometer throughout the remainder of the domain.

The simulation conditions, as in Kapolnai et al. (1996), are detailed as follows. The wave model is forced at the lateral open boundary with a wave field featuring a peak period of 10 seconds, a SWH of 1 m, and a JONSWAP spectral shape. The waves are set perpendicularly to the southern boundary of the domain. Two different boundary conditions are applied to the offshore boundary depending on the type of simulation. If the circulation model is forced only with waves, a zero-gradient boundary condition is enforced along this boundary to simulate an unperturbed sea surface (in this region wave induced set-up/set-down should not be significant). When the circulation is forced with both waves and tides the offshore boundary elevation is modulated with specified M2 tidal component with 0.15 m of amplitudes and zero phase at the boundary.

In Figure 2.3.3 we present a snapshot of the results at the 48-hour timestep from the two uncoupled simulations W-0 (a) and C-0 (c), and the coupled W-C (b and d) simulations, with a magnification on the area of the inlet as indicated in Figure 2.3.1. The area of magnification is reduced in the plots showing the currents to better appreciate the vectors' patterns. In the experiment W-0 (a) the wave field demonstrates an homogeneous SWH of approximately 1.2 m as it approaches the inlet, with a reduction along the boundary of the inlet and a spread of around 60° in the lagoon, reaching a maximum SWH of about 0.8 m at the northern boundary. The W-C experiment (b) displays a markedly different and asymmetric pattern as shown in previous work as Cobb and Blain (2002). The maximum SWH in this domain exceeds 1.4 m,

and at the mouth of the inlet, the SWH is higher than in the uncoupled experiment. The wave spread in the lagoon is larger, around 80° , and the maximum SWH at the northern boundary is lower than the uncoupled simulation, reaching a maximum of 0.5 m. According to the difference in spreading, we can assume that it is caused by wave refraction induced by non-uniform currents, which enhances both physical and numerical spreading. On the other hand, W-0 exhibits reduced numerical diffusion which is a characteristic of the WW3 high-order propagation schemes, as the one used here. Interestingly, the presence of currents in W-C appears to mitigate this phenomenon. The simulation C-0 (c) depicts the currents along the inlet, revealing four small meanders at the corners of the inlet and a central jet flanked by two eddies. Additionally, two large, nearly symmetrical eddies are observed in the lagoon. In the coupled simulation W-C (d), the four meanders shift towards the center, resulting in the formation of two eddies between the meanders and the inlet walls. The central jet is less pronounced compared to the C-0 simulation, and the velocities at the inlet mouth, diverging outward, are more intense. This increased intensity contributes to the rise in significant wave height (SWH) observed in Figure 2.3.3(b). Inside the lagoon, the pattern of two large eddies is less pronounced, and a significant current is observed.

Following the work of Cobb and Blain (2002), we compared different simulations along the transect 1-2 (shown in Figure 2.3.1(b)). In the first validation at the 48-hour timestep, we qualitatively analyze the pattern of SWH from two configurations (Figure 2.3.4(a)). The W-0 configuration well describe the shoaling of waves entering the inlet and lagoon. The SWH exhibits a gradual increase to a maximum of approximately 1.1 m at 20 km from the southern boundary, followed by a reduction to 0.6 m at 30 km. The pattern observed in the coupled experiment W-C aligns with W-0 up to about 16 km, where the waves begin to be influenced by the currents flowing outward from the lagoon. This interaction causes refraction, resulting in steeper and higher waves that exceed 1.3 m around 18 km. As result, the waves begin to break earlier and more intensely, leading to a rapid drop of SWH to 0.6 m at 28 km.

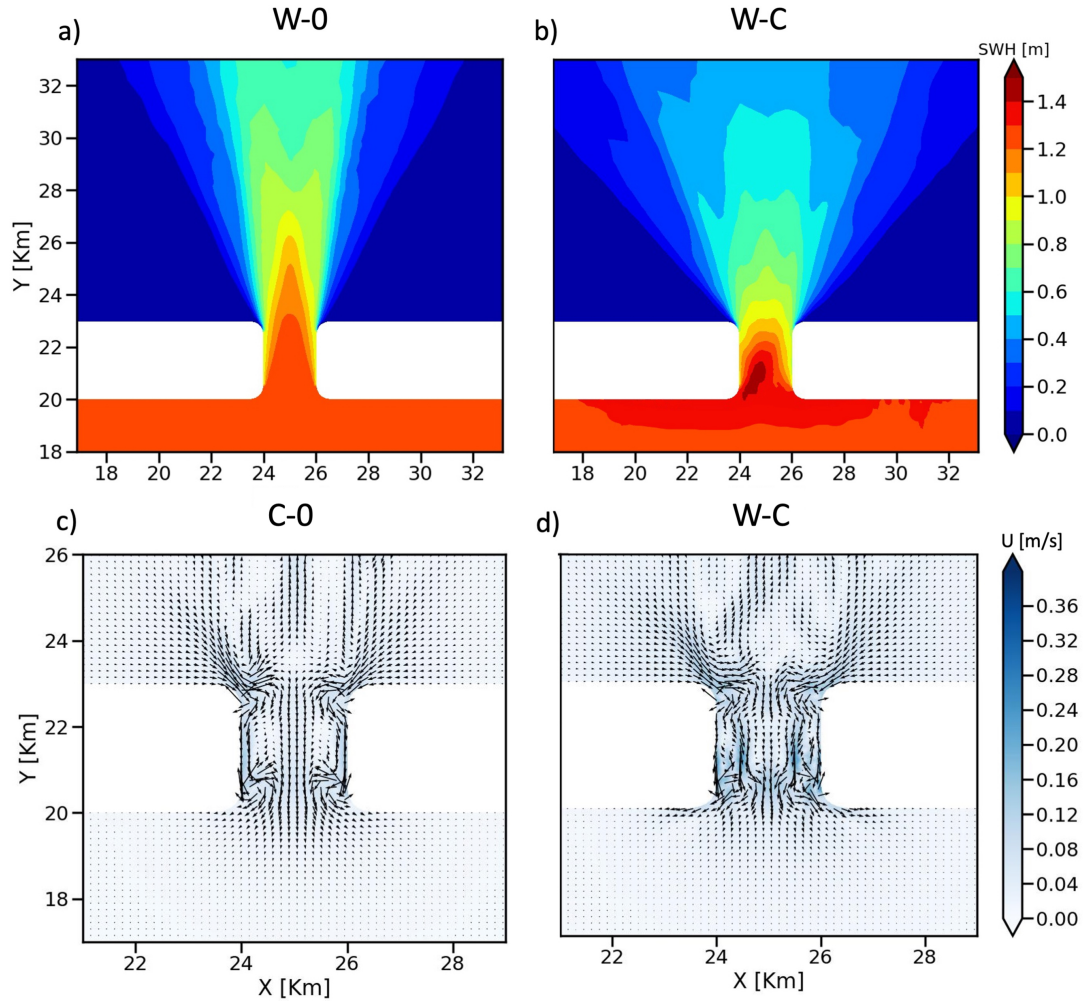


Figure 2.3.3. Wave-forced coastal inlet at steady condition: significant wave height for the wave-only simulation (a) and for the two-way wave-currents coupled simulation (b); currents for the wave-to-current forced simulation (c) and for the two-way wave-currents coupled simulation (d).

Figure 2.3.4(b) effectively illustrates the coastal processes of wave setup and setdown, as well as the complex interaction between currents and waves near the coast. In this plot, the water level is at rest and theoretically should remain constant at 0 m. The impact of wave forcing, namely

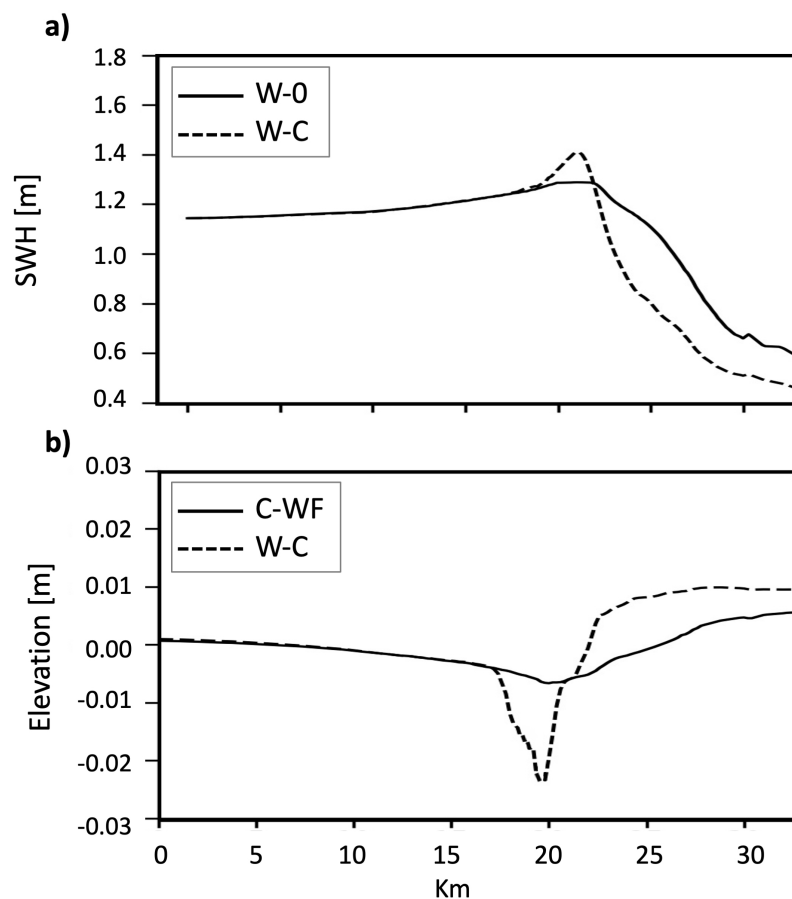


Figure 2.3.4. SWH (a) and water elevation (b) of the transects along section 1-2 as indicated in Figure 2.3.1(b). The figures replicate the Cobb and Blain (2002) simulations: in (a) we compared W-0 and W-C simulations, while in (b) we compared C-WF with W-C experiment.

the contribution of radiation stress to the circulation, is evident from the deviation of water elevation from the rest condition. A setdown corresponds well with the wave shoaling indicated by W-0 in plot (a), reaching approximately -5 mm at 20 km from the southern boundary and +5 mm with a steeper slope at 33 km in experiment C-WF.

Wave setup and setdown are further amplified in the fully coupled configuration W-C, where current-induced refraction and breaking result in a higher momentum flux to the water. This configuration exhibits a negative peak of setdown at -2.5 cm and a positive peak of setup at +1 cm, consistently occurring at around 25 km.

The last analysis of wave-current interaction in an idealized testcase examines the differences between the C-0 and W-C configurations within a tidally driven framework (Figure 2.3.5). During both flood (a) and ebb (b) phases, the smoother tidal profiles observed in C-0 are perturbed by the wave fields interactions in the W-C simulation. The difference between the configurations are slightly larger during the flood phase, around 1.5 cm, and less than 1 cm during the ebb phase of setdown. Both phases indicate a wave setup occurring beyond 22 km.

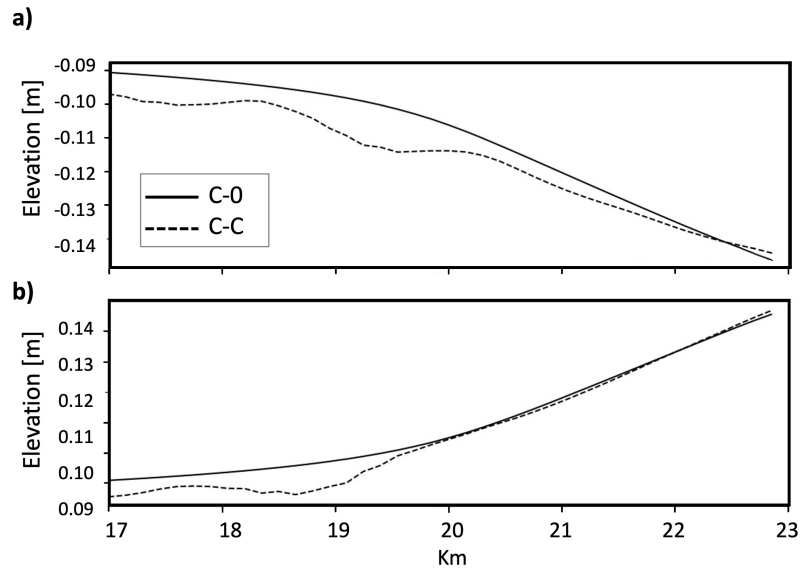


Figure 2.3.5. Magnification (at 17-23 km) of the water level along the transect 1-2 shown in Figure 2.3.1(b) for configuration C-0 and W-C in a tidally-driven framework at the ebb (a) and flood (b) phase.

In all the qualitative validations (Figure 2.3.3, Figure 2.3.4, and Figure 2.3.5), the coupled framework presented in this work produces sea-level responses whose magnitude and spatial

structure are physically consistent with large-scale, rotation-dominated coastal dynamics. Although the simulated water-surface gradients are small in absolute terms, such gradients are sufficient to balance Coriolis effects and to contribute to large scale, rotation dominated flows with velocities of order $\mathcal{O}(10^{-1})\text{m s}^{-1}$, which are significant at shelf and basin scales. The consistency of these magnitudes and patterns with previous numerical and theoretical studies (Cobb and Blain, 2002; Wu et al., 2011; Xia et al., 2020) supports the robustness of the coupled model formulation and motivates its application to real-case events, where the cumulative impact of such gradients over large spatial scales is expected to become dynamically important.

2.4 Wave-circulation fields during Medicane Ianos

Medicane Ianos, is one of the most intense Mediterranean storms since the onset of satellite observation (Von Schuckmann et al. (2022)). It is notable for its duration and severity, resulting in significant rainfall, flooding, damage, and fatalities (Zekkos et al. (2020)). It originated off the Libyan coast near the Gulf of Sidra on September 14th, 2020, and moved toward the Ionian Sea and Greece between September 17th and 20th. The storm intensified as it moved northward and eastward, reaching peak strength on September 16th and passing through central Greece, particularly impacting the regions around Karditsa and Farsala. Ianos eventually weakened as it shifted southeast towards Crete. With wind speeds reaching 110 km/h, the storm caused widespread flooding and destruction, leading to four fatalities in Greece and substantial damage, including the flooding of approximately 5000 properties in Karditsa alone (a slew of weather events – including two named storms troubling Europe – pose challenges far and wide; Yale Climate Connections, 2024).

2.4.1 Set-up of the model

The numerical domain, shown in Figure 2.4.1, encompasses the entire central South Mediterranean Sea, with three open lateral boundaries: in the Otranto Channel to the North, the Sicily Strait to the West, and the Ionian Sea (between Greece and Libya) to the East. The domain is discretized with an unstructured grid, featuring a horizontal resolution of approximately 2 km offshore, 1 km along the coasts, and 50 m in the area where Medicane Ianos made landfall in Greece, including the islands of Zakynthos and Kefalonia.

The circulations and wave models are forced with atmospheric fields from ECMWF analysis data (10 km resolution and 6h frequency). The surface fields are corrected along the coastal boundaries following the sea-over-land procedure described in Kara et al. (2008). The atmospheric variables used for the circulation include 2 m air temperature, 2 m dew point temperature, total cloud cover, mean sea level atmospheric pressure, and total precipitation. Meridional and zonal 10 m wind components are used for both wave and circulation models. The modelling approach is based on the downscaling of Copernicus Marine Service (CMEMS) products released at the Mediterranean Sea regional scale. The circulation model is three-dimensionally nested into MEDSEA_MULTIYEAR_PHY product (Table 2.4.1) both in terms of initialization and open boundaries. The scalar fields (sea level, temperature, and salinity) are treated through a clamped boundary condition, while the velocity fields are imposed as nudged boundary condition using a relaxation time of 3600 s.

The wave model is initialized using a parametric fetch-limited spectrum based on the initial wind field and is forced at the lateral open boundaries by the MEDSEA_MULTIYEAR_WAV product (Table 2.4.1). Mean wave parameters, such as significant wave height, mean wave direction and peak period, are used to reconstruct the wave spectra, following the approximation described by YAMAGUCHI (1984). The model outputs are saved at 1-hour frequency.

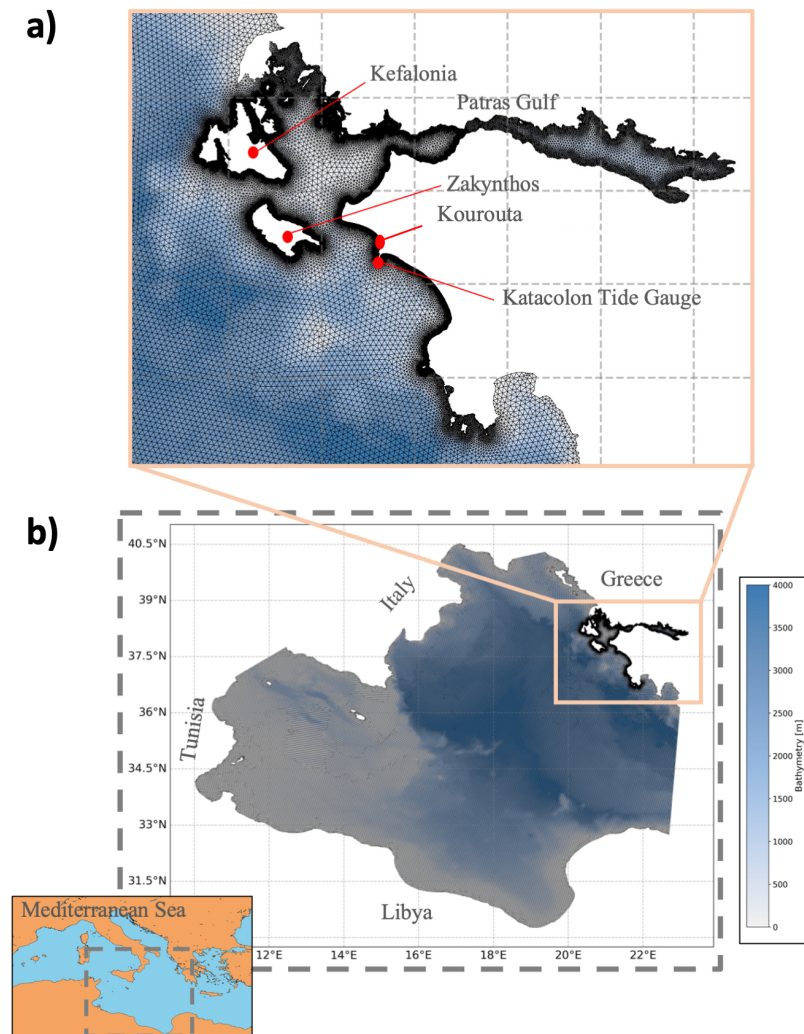


Figure 2.4.1. Spatial unstructured-grid and bathymetry for the Ionian Sea (b) used for the Ianos Medicane simulation, with an enlarged view on refined areas of affected area (a).

Table 2.4.1. Datasets used in this study.

Datasets	Provider	Usage	Website
MEDSEA_MULTIYEAR_PHY (Escudier et al. (2020))	Copernicus Marine Service	Circulation model lateral boundary	https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1
MEDSEA_MULTIYEAR_WAV (Korres et al. (2023b))	Copernicus Marine Service	Wave model lateral boundary	https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_WAV_006_012_CLIM
SST_MED_SST_L4_REP_OBSERVATIONS (Pisano et al. (2016); Embury et al. (2024))	Copernicus Marine Service	SST anomaly evaluation	https://doi.org/10.48670/moi-00173
WAVE_GLO_PHY_SWH_L3_NRT (WAVE_GLO_PHY_SWH_L3_NRT_014_001, 2025)	Copernicus Marine Service	Wave validation	https://doi.org/10.48670/moi-00179
Katakolon tide gauge (Holgate et al. (2013))	Permanent Service for Mean Sea Level	Sea level validation	https://psmsl.org/data/obtaining/stations/1240.php
EMODnet bathymetry 2020 (EMODnet Bathymetry (2020))	EMODnet	Model bathymetry	https://doi.org/10.12770/bb6a87dd-e579-4036-abe1-e649cea9881a
IFS010 (Bidlot and Janssen (2024))	ECMWF	Atmospheric forcings	https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

2.4.2 Synoptic overview and results

The Medicane Ianos reached its maximum intensity at 18:00 on September 16th, 2020, as it entered the Ionian Sea (Figure 2.4.2). The coupled modelling framework provides a comprehensive analysis of the event, revealing the storm's extensive impact on the wave field across the central Mediterranean Sea. The affected area spans over $5^\circ \times 5^\circ$, with significant wave heights averaging over 3 m and reaching up to 6 m in the eyewall region (Figure 2.4.2(a)). The Medicane's influence on sea level is clear, as a pronounced positive sea level anomaly exceeding +20 cm is observed, particularly within the storm's core (Figure 2.4.2(b)). This anomaly stands out against the low-tide conditions, providing a distinct footprint of the storm. Although sea surface temperature do not exhibit a consistent pattern at the storm's peak, cooler waters are noticeable in the southeastern region of Sicily (Figure 2.4.2(c)). Additionally, the sea surface currents display a well-defined pattern, with velocities exceeding 1 m/s along the eyewall and a divergent flow branching northeastward and southeastward (Figure 2.4.2(d)).

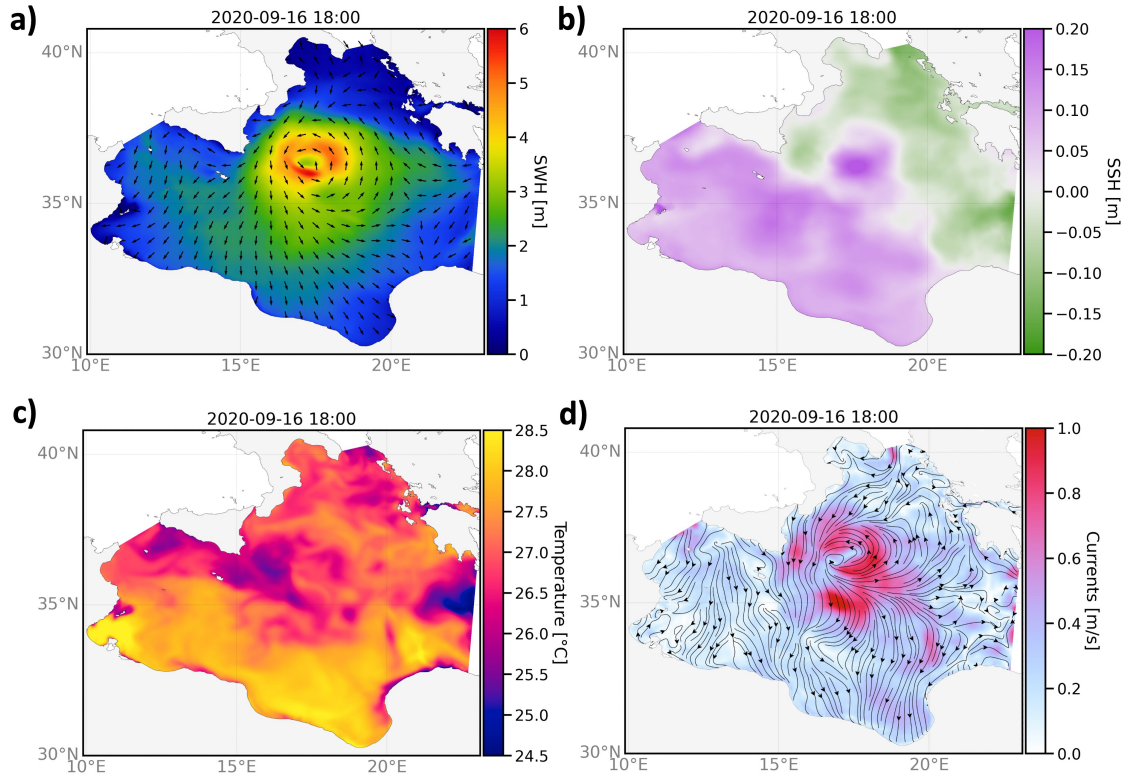


Figure 2.4.2. Maps of significant wave height (a), sea level (b), sea surface temperature (c) and surface circulation (d) on 2020-09-16 18:00 UTC (peak time in open ocean) for the entire domain from two-way coupled simulation.

At 06:00 on the 18th of November, the Medicane made landfall in Greece, impacting the islands of Zakynthos and Kefalonia, as well as the Gulf of Patras (Figure 2.4.3). The SWH simulated during this event, as shown in Figure 2.4.3(a), is notably high for this region of the Mediterranean, reaching up to 4.5 m along the western coastlines of the islands. The cyclonic circulation associated with the Medicane intensifies the waves on the northern part of the Gulf of Patras, which is particularly affected due to the nearly perpendicular wave direction. Furthermore, the confluence of currents from the north and south of Zakynthos (Figure 2.4.3(b)) results in current speeds reaching up to 1.2 m/s in this convergence zone. The combined action

of enhanced wave forcing, and strong currents produces a storm-surge contribution exceeding 30 cm in the northern part of the Gulf of Patras (Figure 2.4.3(c)). Although moderate in absolute terms, this surge magnitude represents a substantial fraction of the total water-level variability typically observed during Mediterranean extreme events and is consistent with reported impacts during Medicane Ianos, including extensive flooding over low-lying coastal areas and seawater run-up extending up to 200 m inland (Androulidakis et al., 2023).

In the following sections, we investigate the effect of the coupling on the simulation of the Medicane.

2.4.2.1 Effects of circulation on waves

The validation of the wave model results and the difference between the W-C and W-0 configurations are shown in this paragraph using two approaches. In Figure 2.4.4 we compare the simulations with the satellite altimeter tracks (WAVE_GLO_PHY_SWH_L3_NRT, Table 2.4.1) which crossed the Medicane. In details, three altimetric measurements from Jason-3, SARAL-Altika and Sentinel-3B are available on the 17th September, and the SWH results from the W-C configuration are overlapped with the satellites measurement and shown in Figure 2.4.4 (a),(b),(c) respectively. The model simulates the extreme event with a very high quality, and the patterns of the modeled wave field match with good agreement the satellite data. For Jason-3 and Sentinel-3B the measured SWH reaches 5 m, while for SARAL-Altika, the SWH is slightly lower because the track is slightly eastward to the Medicane. Figure 2.4.4 panels (d), (e), and (f) illustrate the along-track validation for both the W-C and W-0 configurations. This analysis is based on the nearest point between observation and model in both space and time dimensions. The difference between the two configurations can be a few tens of centimeters in some cases, while in others, the time series overlap. However, the W-C configuration demonstrates a reduction of approximately 3-4% for the Root Mean Squared Error (RMSE) for Jason-3 (d) and Sentinel-3B (f) tracks. It is worth mentioning that, although this analysis shows better peak

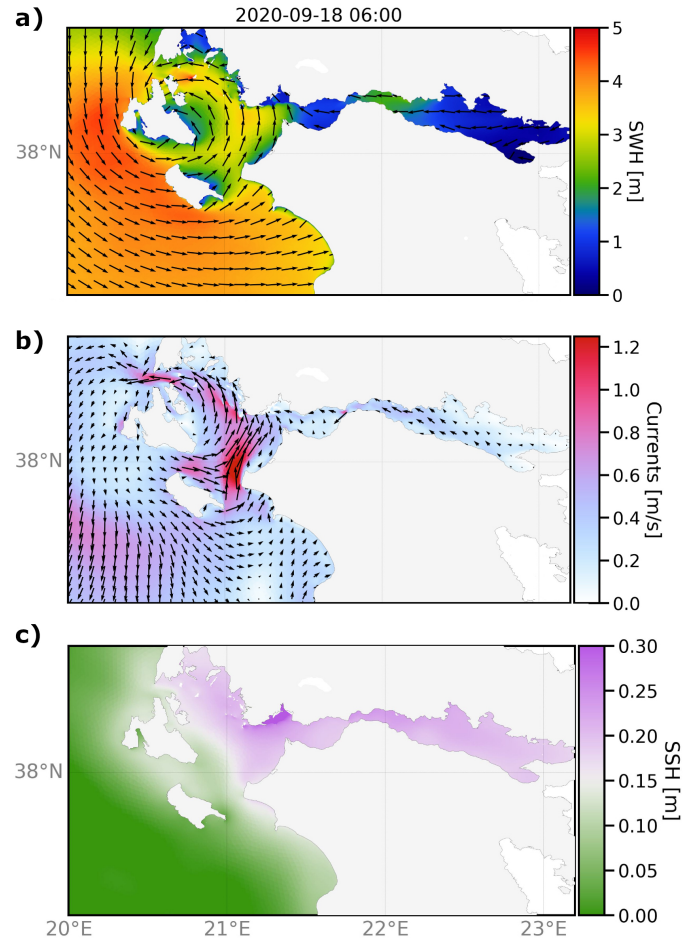


Figure 2.4.3. Maps of significant wave height (a), surface circulation (b) and sea level (c) on 2020-09-18 06:00 UTC (peak time in coastal zones of Greece) for the Greek coastal areas from two-way coupled simulation (W-C).

predictions for the W-0 configuration, the W-C configuration more closely matches the observations overall, both during growth and decay phases. A potential motivation for the reduction of SWH at peaks in the coupled experiment is due to the alignment of currents and wind, which reduces wind stress. This is attributed to the fact that the absolute wind speed used to force the wave model is modified into relative wind by the presence of currents.

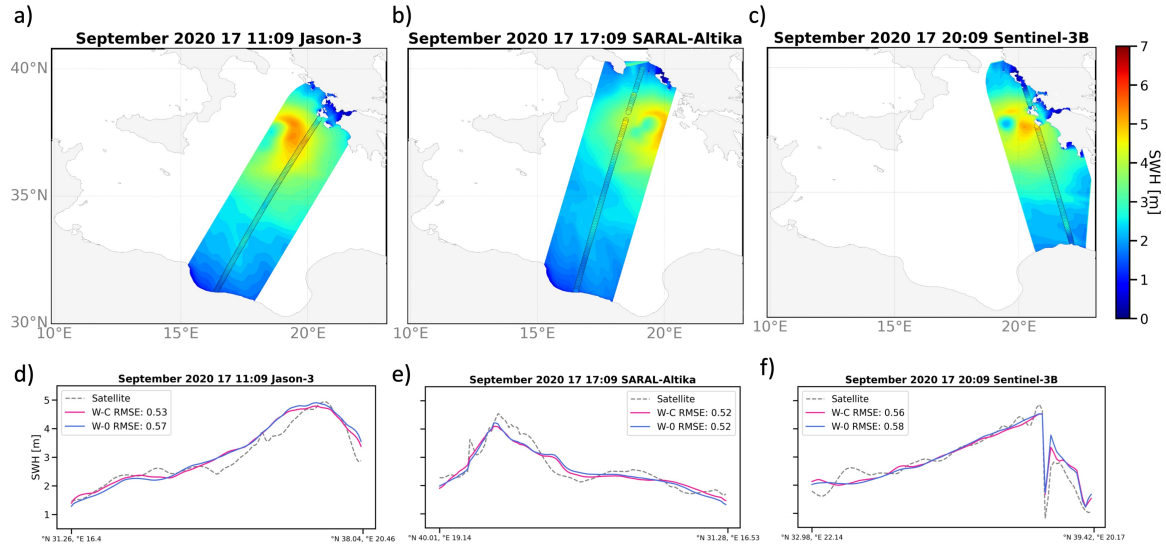


Figure 2.4.4. Maps of SWH against satellite altimeter (Jason3, Saral-Altika, Sentinel-3b) tracks (inset circles) for the W-C configuration (a) (b) (c). SWH along-track comparison between the two model configurations and satellite tracks is reported in (e), (f) and (g).

For a more robust assessment of the wave model, we analyze the time window including the days the Medicane Ianos persisted over the central Mediterranean Sea, from September 15th to 19th (Figure 2.4.4). From this investigation, the model exhibits a very high accuracy in representing the extreme event, with a correlation coefficient of 0.95, a negative bias of approximately 20 cm, and a RMSE of 33 cm. The W-C / W-0 comparison shows a reduction in bias of around 6% and a decrease in error of approximately 3% in the coupled configuration, confirming the previous findings of Causio et al. (2021). In this study, we do not present through attribution simulations the explicit quantification of contribution of the air-stability parameter and currents. This decision is based on our prior investigations, which have already demonstrated its effectiveness and role (Causio et al. (2021); Clementi et al. (2017)).

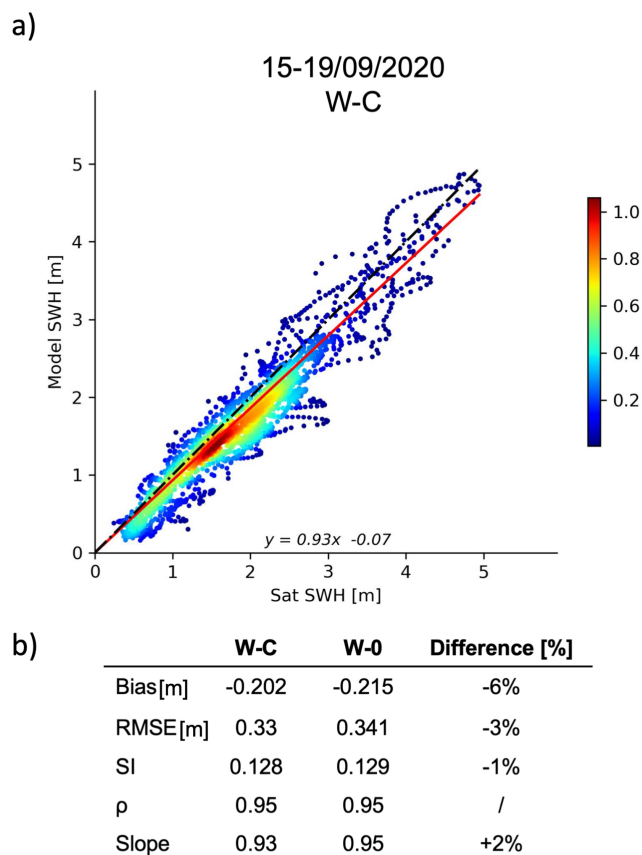


Figure 2.4.5. (a) SWH scatter plot for the W-C configuration is shown, with colors indicating the plot density of occurrence. The black line represents the best-fit line, while the red line denotes the linear regression of the data. (b) Statistics (Root Mean Squared Error – RMSE, Bias, Scatter Index – SI, Pearson’s correlation coefficient – ρ , and the slope of the fit) are summarized and expressed in meters, providing comparisons for the W-C and W-0 configurations as well as the percentage difference between them.

2.4.2.2 Effects of waves on circulation

In Figure 2.4.6 we illustrate the drag coefficient (C_d) from the W-C (Figure 2.4.6(a)) and C-0 (Figure 2.4.6(b)) configurations at the peak of the event (16th September 2020 at 18:00) and

their differences (Figure 2.4.6(c)). The C_d from the uncoupled simulation, which is derived from the Hellerman and Rosenstein (1983) formulation, exhibits a more homogeneous field and overall higher values with respect to the coupled system, except in the area of the Ianos passage at the peak time, where the coupled simulation is able to provide larger C_d values. Significant differences between the sea-state dependent drag (W-0) and the Hellerman and Rosenstein (1983) formulation (used in C-0) occur in regions farther from the Medicane (see Figure 2.4.2(a)), particularly in the Northern Ionian Sea, the eastern part of the study domain, and the Gulf of Gabes. Additionally, the wider range for C_d allows to reach higher values; the C-0 configuration never exceeds the value of 2.5×10^{-3} , while the W-C configuration goes beyond 3.5×10^{-3} . In both configurations, the pattern of extreme drag is asymmetric, with the southern part of the Medicane experiencing the highest values.

The passage of a strong cyclone over a water body induces surface cooling due to both upwelling and increased evaporation (Price (1981)). In Figure 2.4.7, we present the Sea Surface Temperature (SST) footprint induced by Ianos' passage over the central Mediterranean Sea, following the approach of Clementi et al. (2022). The footprint results from the comparison of the SST of the day after the Medicane hit Greece (19th September) with the SST of the day before Ianos' formation (14th September). The footprint is computed for L4 gridded satellite observations (Table 2.4.1) (Figure 2.4.7(a)), W-C configuration (Figure 2.4.7(b)), and C-0 configuration (not showed). Additionally, the difference between the footprints of W-C and C-0 is shown in Figure 2.4.7(c). Specifically, for the satellite data, the foundation temperature is used, which approximately corresponds to the sea temperature during the night-time at a depth of around 2-5 m. For this reason, in this analysis we used the model temperature at midnight at a depth of 3 m.

The SST footprint from satellite shows a general cooling of the central Mediterranean Sea, with the exception of the southern coasts, and two distinct areas of larger significant cooling. The southern Ionian Sea, where the Medicane experiences its highest intensity, shows the largest

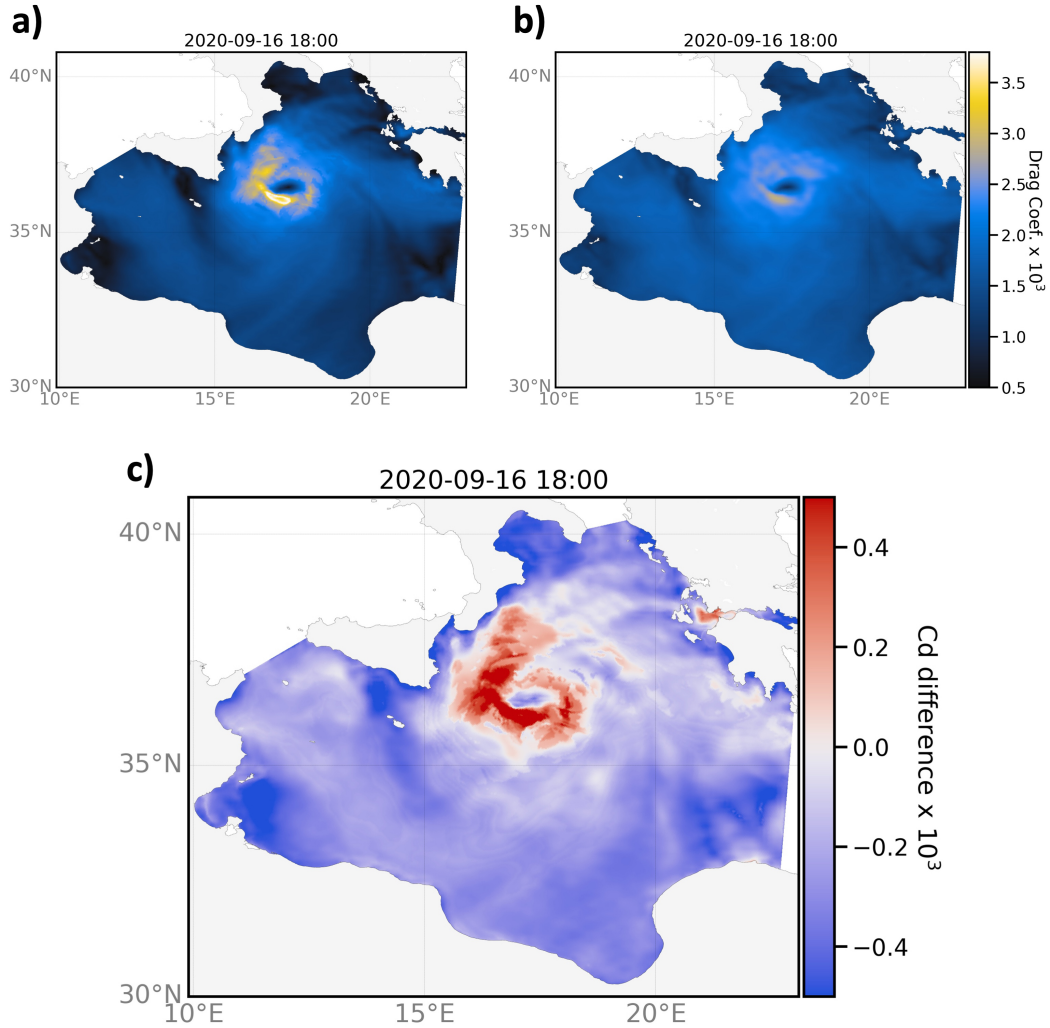


Figure 2.4.6. Maps of drag coefficient (C_d) at the peak event in open ocean (2020-09-16 18:00). (a) Drag coefficient computed by WW3 in the W-C experiment. (b) Drag coefficient computed via Hellerman and Rosenstein (1983) in the C-O experiment. (c) Difference between (a) and (b).

cooling, dropping the temperature down by -5°C . Here the footprint follows the Medicane track with a northeast orientation. A qualitative comparison between the satellite data and the W-C and C-0 configurations illustrate that both configurations exhibit adequate patterns but

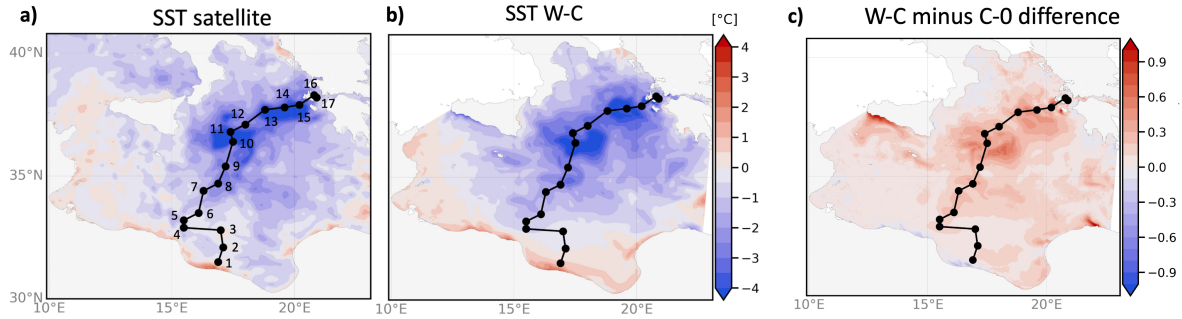


Figure 2.4.7. Sea surface temperature anomaly [$^{\circ}\text{C}$] between 19th Sept. (after Ianos) and 14th Sept. (before Ianos) from satellite (a), two-way coupled model W-C (b), and SST difference between the anomaly of W-C and C-0 (c). The black path represents the Medicane Ianos path identified as minimum sea level pressure location every 6 hours. In panels (a) and (b) the colorbar range is set to $[-4, 4\text{ }^{\circ}\text{C}]$ to better highlight the footprints pattern, even though the difference reached $-5\text{ }^{\circ}\text{C}$.

show a stronger impact on SST compared to the observations. However, the W-C configuration demonstrates slightly warmer behavior (Figure 2.4.7(c)), and the footprint's width is narrower than in C-0, more closely matching the pattern observed in satellite data. These differences can be attributed to the sea-state dependent drag coefficient which modifies the circulation in the area. Furthermore, Figure 2.4.7 shows the path of the medicane as it passed through the Ionian Sea (from Libya at point 1 to Greece at point 17), highlighting the location of the sea level pressure minimum every 6 hours.

Consequently, we analyze the vertical profile of model temperature along the Medicane track (Figure 2.4.8) for both the W-C and C-0 configurations. In this assessment we compute, as in Figure 2.4.7, the temperature anomaly between 19th and 14th September, and then, the difference between W-C and C-0. The range of temperature anomaly spans from approximately -0.6 to $0.6\text{ }^{\circ}\text{C}$. Notably, the largest difference between the two configurations occurs in the Ionian Sea, particularly from point 10 onward. Throughout the track, the W-C configuration is warmer in the mixed layer, being the latter generally slightly shallower in the coupled simulation, with a few exceptions at points 3 and 14 where the uncoupled configuration exhibits a slightly thin-

ner mixed layer. As Medicane Ianos moves towards Greece, the plot indicates that the W-C configuration footprint is even warmer in the mixed layer than C-0, and even colder below the pycnocline, suggesting a strengthening of the stratification in W-C. Point 13 and 14 are peculiar because they show warmer W-C even below the mixed layer up to 60 m. This difference can be attributed to the less intense upwelling observed in the W-C configuration, which results in smaller cold wedges (located at points 10-12 and 13-15 in Figure 2.4.7) compared to those in the C-0 configuration.

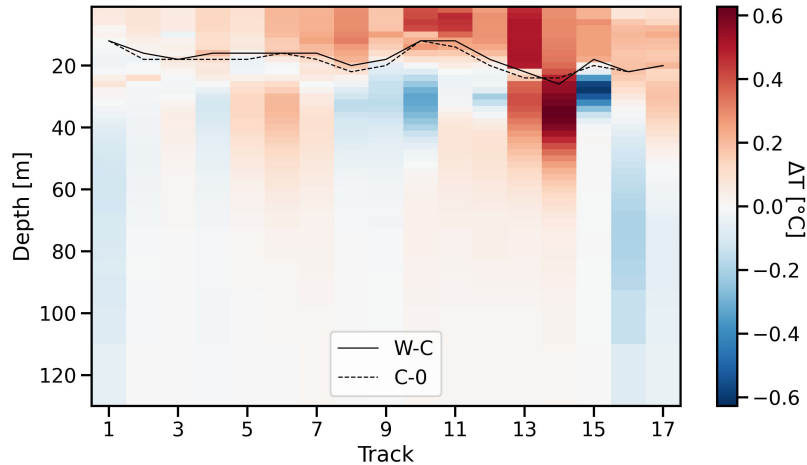


Figure 2.4.8. Anomaly Temperature difference between W-C and C-0 for the Medicane Ianos passage over the central Mediterranean Sea. Black lines refer to the mixed layer depth for W-C (solid line), and C-0 (dashed line). The x-axis corresponds to the locations shown in Figure 2.4.7(a).

These results indicate that the impact of coupling on the vertical thermal structure is largely confined to the upper mixed layer, approximately 50 m, along the offshore portion of the Medicane track. In contrast, at coastal track locations, coupling-induced temperature anomalies locally penetrate deeper, reaching depths of approximately 100 m, as evidenced at points 1 and 17 in Figure 2.4.8. The deeper penetration observed near the coast reflects localized dynamics rather than a basin-wide response. One of the main contributions of the coupled modelling

framework is the improved representation of coastal total water level extremes through the inclusion of wave-induced radiation stresses, which generate wave setup and modify nearshore circulation during storm conditions. Sensitivity tests with C_d + radiation stress and radiation stress only showed differences below 1%, while the C_d -only case closely matched the W-0 simulation (results not shown).

Medicane Ianos was chosen for this study because it made landfall close to the Katakolon tide gauge, which provides a suitable reference for comparison between the sea level observations and the W-C and C-O configurations (Figure 2.4.9). The C-0 configuration demonstrates good accuracy in predicting sea level at the tide gauge location; however, the W-C configuration represents more accurately the storm surge induced by the Medicane (the event is highlighted in yellow in Figure 2.4.9(a)). Both configurations show nearly identical performance under normal conditions (before and after the event). The maximum difference between the two configurations is 4 cm, allowing the W-C configuration to simulate more precisely the two peaks of the storm surge. Notably, the inclusion of wave effects lead to a more rapid drop in surge after the storm passage, improving also the fit for the first tide trough after the storm (the third tide trough within the yellow area in Figure 2.4.9(a)). It is worth mentioning that the wave contribution to the Ianos storm surge is approximately 10% at the peak of the event, although this value can be significantly higher in other situations. To illustrate this, Figure 2.4.9(a) bottom panel shows the same time series comparison for a location few km far from the tide gauge, along the nearby beach of Kourouta. The plot reveals that the waves provide a larger contribution in this location, resulting in a surge about 11 cm higher than the one showed in C-0, accounting for roughly 30% of the total contribution. The difference between the timeseries, as shown in Figure 2.4.9(c), can be attributed to the wave field direction, which makes the tide gauge partially sheltered, while the beach faces more orthogonal waves. The significance of wave direction is further emphasized along the northern shoreline, where the wave setup is even more intense due to the waves being nearly orthogonal to the coast.

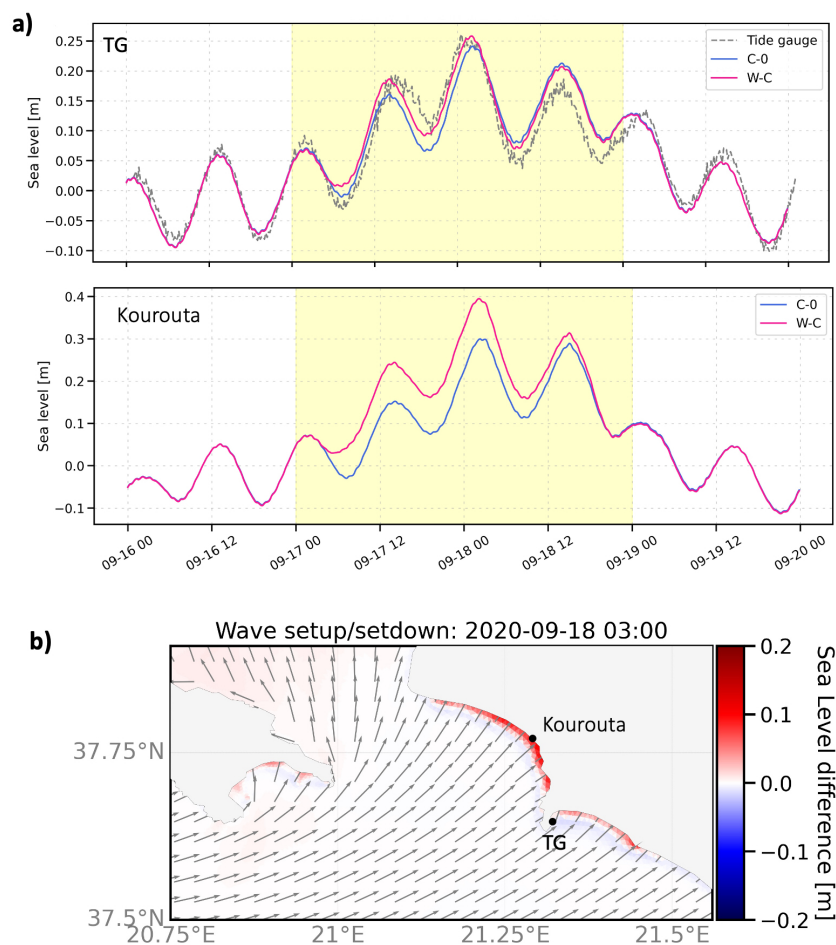


Figure 2.4.9. Timeseries of TWL for C-0 and W-C configurations. In plot (a) upper panel, the model are compared with observed data at Katakolon tide gauge -TG (in dashed gray). In the plot (b) bottom panel, the model configurations are compared at the Kourouta beach. The shaded yellow area highlights the two days impacted by the Medicane induced surge. Plot (b) highlights the wave setup (in red) and setdown (in blue), computed as the TWL difference between C-0 and W-C. Additionally, it shows the location of the timeseries (in plot a), as well as the mean wave direction represented by vectors.

Notably, the wave contribution to the storm surge during the Medicane Ianos is comparable in percentage to findings of Dietrich et al. (2011) for Katrina and Rita hurricanes in the Gulf of Mexico, and Kim et al. (2010) during Typhon Anita in South China Sea.

2.4.2.3 Computational performance and parallel reproducibility

We provide additional details on the coupling procedure performance. The coupled system is more computationally demanding than the individual models, with the computational time of the coupled system approximately 30% longer than that of the standalone wave model. We emphasize the wave model because it represents the primary bottleneck between the two models. While this increase in computational time was not a major concern in our study or in operational use, refactoring the system to improve performance could be beneficial for long hindcast applications. Regarding CPU-coherency, we conducted a twin simulations using 144 and 216 cores and compared the results. The average difference for all the output variables over the 7-day simulation is as in the next table:

Table 2.4.2. Summary of the average differences in the investigated variables after a 7-day simulation using 144 and 216 cores.

	Temperature	Salinity	Water Level	u velocity	v velocity	SWH
Difference 144-216 cores after 7 days	-3.45e-06	-9.81e-06	6.02e-06	7.28e-06	-1.09e-06	-1.35e-07

The Figure 2.4.10 illustrates the time evolution of the difference in selected variables (not all, to maintain clarity) between the two simulations. The discrepancies stabilize around 10^{-6} - 10^{-5} after two days of simulation. For this type of application, these results are satisfactory, especially considering that SHYFEM-MPI was not compiled with the bit-wise reproducibility option and that the error remains within the limits of single-precision floating-point operations.

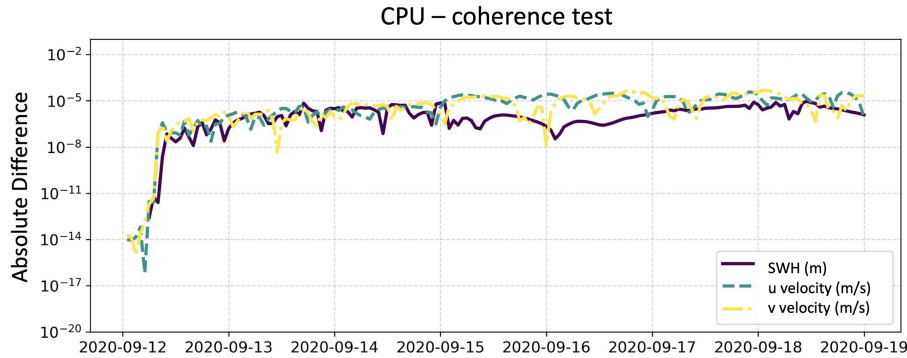


Figure 2.4.10. Error evolution over a 7-day simulation for u and v components and SWH, using 144 and 216 cores.

2.5 Discussion

Our primary goal is the evaluation of storm surge dynamics, nevertheless, together with radiation stress, we incorporated also additional coupled physical processes, such as sea-state-dependent wind stress, doppler shift, sea-level-dependent water depth for wave physics, and the inclusion of effective wind based on air stability parameters.

The real-case simulation and comparison of coupled versus uncoupled configurations highlight the added value of incorporating the wave component in storm surge simulations, particularly for coastal applications. Notably, during Medicane Ianos, wave setup contributes to approximately 10% of the sea level variation at the Katakolon tide gauge, with a significantly greater impact, around 30% in nearshore areas. The inclusion of sea-state-dependent drag coefficient introduces a larger dynamics to the simulations, with a lower drag in areas distant from the storm and increases drag near the eyewall of the Medicane.

Our findings indicate that the coupling effects are more pronounced in the northern part of the Medicane’s path, where the storm intensity is largest. The coupling leads to a slightly thinner and warmer mixed layer and, in some locations, affects the water column up to 100 m, likely due to reduced upwelling of deeper waters. The impact of circulation on wave dynamics is

appreciable, as coupling reduces bias by approximately 6% and overall error by around 3% in the wave model.

The numerical framework developed in this study proves to be an effective tool for simulating both large-scale and coastal processes, with a particular strength in describing storm surge dynamics. This system holds significant potential for enhancing coastal hazard identification, early warning systems, and the management and planning of sea and coastal activities. The encouraging results from this work lay the foundation for further development, including the integration of additional processes such as Stokes drift, sea-state-dependent vertical mixing, and bottom stress (their importance has been shown in several studies as in Breivik et al. (2015); Alari et al. (2016); Staneva et al. (2017); Couvelard et al. (2020)), which are currently neglected or parameterized in this version of the circulation model.

Chapter 3

Modelling vegetation-induced wave attenuation

Building on the core coupled framework introduced in Section 2, Figure 2.0.1, we extend WW3 to include a vegetation-induced bottom dissipation that represents benthic boundary layer processes, explicitly accounting for plant flexibility and seasonal canopy dynamics (Figure 3.0.1).

The following section is dedicated to the recent publication of Shirinov et al. (2025) in the journal of Natural Hazards and Earth System Sciences. It investigates wave attenuation induced by the nonlinear interactions between wave dynamics and aquatic vegetation along the Civitavecchia coastal zone (north-eastern Tyrrhenian Sea, Italy). Particularly, the study focuses on the seagrass species *Posidonia oceanica*, which is endemic to the Mediterranean Sea and forms extensive meadows that play a crucial role in coastal protection. Their presence helps mitigate wave activity, resulting in the dissipation of wave energy through mechanical work on stems, determined by vegetation traits such as shoot density, canopy height, stiffness, and bending, as well as wave characteristics. The study employs a digital twin approach that enhances model fidelity by coupling numerical simulations with long-term in situ measurements. The results quantify how seasonal variability of the meadows modulates wave damping capacity.

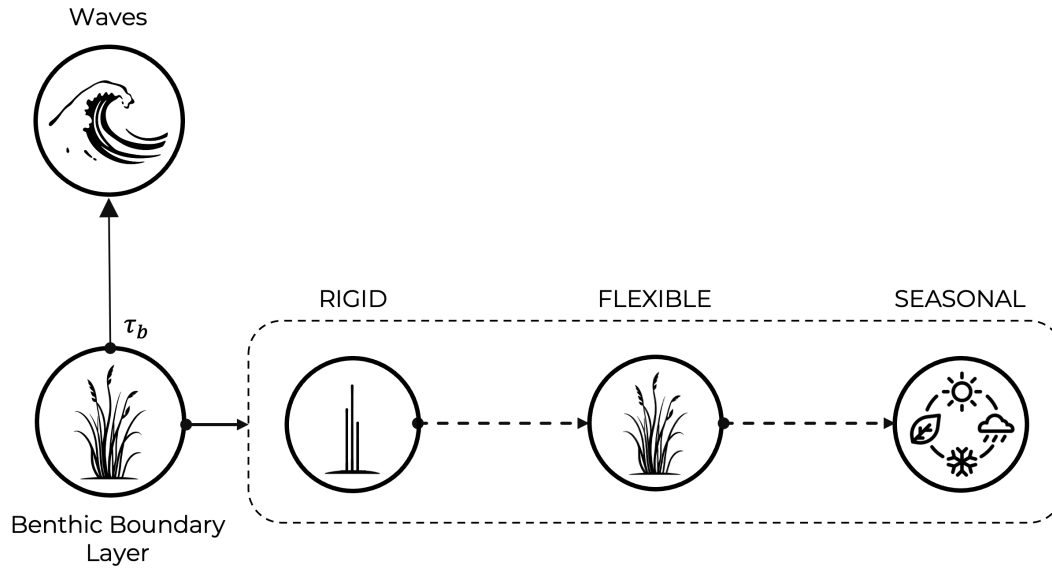


Figure 3.0.1. The benthic boundary layer represented through wave-vegetation interaction mechanisms forming a part of the multi-model framework (Figure 1.3.1). The vegetation-induced drag is provided through advancing the rigid formulation onto (i) flexible one, introducing blade bending mechanisms, and further (ii) seasonal, with intra-annual variability of the canopy height. The latter is informed by in situ observations.

3.1 Concepts of wave-canopy dynamics and objectives

It is widely acknowledged that vegetation meadows help mitigate wave activity. This phenomenon is observed across various marine habitats, including seagrass beds (Infantes et al. (2012), Paul et al. (2012), Sánchez-González et al. (2011)) wetlands (Zhang et al. (2020)), and seaweed communities (Dubi and Tørum (1994), Løvås and Tørum (2001)). Wave-vegetation interactions result in the dissipation of wave energy through mechanical work on stems, determined by vegetation traits such as shoot density, canopy height, stiffness, and bending, as well as wave characteristics. The process known as wave damping, as described by Dalrymple et al. (1984), effectively reduces wave height. Consequently, the reduction in wave height leads to a localized drop in sea surface elevation in the lee of the vegetation patch as demonstrated

by Beudin et al. (2017). Additionally, the mean wavelength increases over the seagrass canopy rather due to the attenuation of shorter waves from the spectrum. This effect, combined with the reduction in wave height, leads to a decrease in wave steepness.

3.1.1 First experimental and numerical models

Numerous numerical studies have investigated wave attenuation by submerged coastal vegetation, with early models frequently simplifying flexible plants as rigid cylinders with varying drag coefficients. Mendez and Losada (2004) formulated an empirical model incorporating wave damping and breaking across vegetation fields of various depths. Suzuki and Dijkstra (2007) employed a volume of fluid (VOF) model to simulate wave attenuation over different beds and vegetation fields, underlining the necessity for further validation concerning the intricate interplay between storm waves and seagrass-induced wave attenuation. Recently, Pillai et al. (2022b) evaluated the role of seagrass as a nature-based solution (NBS) by incorporating the wave damping sink term induced by vegetation into the wave action density spectrum equation within the WW3 wind wave model, following the approach of Beudin et al. (2017). This development was tested in a coastal region of the Northern Adriatic Sea, where the study identified limitations associated with modelling seagrass as rigid stems, resulting in excessive wave damping. The authors hypothesized that accounting for plant flexibility would yield more realistic outcomes, and a reduced damping capacity compared to rigid formulation. Similarly, Abdolali et al. (2022), through the implementation of the vegetation term in WW3, concluded that excluding the vegetation sink term in marsh environments leads to significant discrepancies between model outputs and observations. Jacob et al. (2023) reached analogous conclusions regarding the application of the SCHISM-WWM modelling framework in conjunction with a rigid vegetation module for the coastal waters of the German Wadden Sea. Luhar and Nepf (2016) sought to develop a physics-based model to predict wave decay in a submerged meadow, accounting for the adaptive responses of flexible plants to wave orbital excursion.

3.1.2 Flexible formulation and seasonal variability

To investigate how flexibility can enhance model performance and, consequently, increase the model's ability to replicate the behavior of seagrass meadows in wave attenuation, specific *in situ* measurements within submerged vegetation are essential. The lack of detailed observational data on vegetation characteristics, such as morphology and mechanical properties, poses a challenge (Luhar and Nepf (2016)). Instead, existing models often rely on generalized literature data, which may not fully capture the nuances of different plant species. Moreover, these models tend to overlook seasonal variations in vegetation properties, despite growing evidence of their importance in coastal processes (Jacob et al. (2023)). So far, wave attenuation by seagrass canopies has been primarily measured during experiments in flumes using canopy mimics (Sánchez-González et al. (2011); Manca et al. (2012); Stratigaki et al. (2011); Lei and Nepf (2019); Vettori et al. (2024)). Limited field measurements have been conducted in meadows due to challenges in deploying and maintaining instruments and platforms in underwater environments that can withstand intense weather events (Fonseca and Cahalan (1992); Bradley and Houser (2009); Infantes et al. (2012)). A recent study by Contti Neto et al. (2025), using extensive high-resolution flow measurements, concluded that accounting for flow-induced deflection of seagrass blades, which alters effective canopy height, significantly improves wave dissipation predictions.

In this study, we combine numerical simulations with observational data to emphasize the need for continuous monitoring and the effective integration of empirical measurements into numerical models. This holistic approach not only enhances the precision of the simulations but also represents a pivotal aspect of the coastal digital twin methodologies, necessitating interaction between real-world data and numerical models (Jeong and Lee (2023)). Ultimately, such synergy seeks to facilitate informed decision-making in dynamic marine environments, supporting forecasts of environmental extremes to aid in risk assessment and management, while also advancing our understanding of the resilience of NBS systems.

The seagrass species considered in this work is *Posidonia oceanica* (*P. oceanica*) that stands out as the most common seagrass species in the Mediterranean Sea, typically found in shallow sub-tidal waters up to a depth of 50 meters under clear conditions (Borum et al. (2004)). Submerged plants increase bottom roughness, reducing near-bed velocities and altering sediment transport (Madsen et al. (2001)), while also enhancing wave attenuation (Mendez and Losada (2004)). On a long timescale the numerical simulations of waves over marine seagrasses have so far been conducted using vegetation parameters that remain constant in space and time (Pillai et al. (2022b)). Given that *P. oceanica* meadows along the coastal areas exhibit varying characteristics depending on the type of substrate they inhabit (e.g. rock, sand, and degraded matte), it is necessary to consider the spatial and temporal variability of vegetation parameters (shoot density and leaf length) to accurately estimate the wave damping effect. *P. oceanica* meadows grow on an inter-annual scale by branching rhizomes horizontally to colonize vacant substrates when environmental conditions are favorable, and vertically to prevent siltation. On a seasonal (intra-annual) scale, above-ground biomass production occurs through leaf growth, reaching maximum length in summer and minimum in winter. Over the years, many models of varying complexity have attempted to reproduce the growth of marine seagrasses by developing growth curves for leaves during different seasonal periods (Ott (1980)), utilizing the concept of architecture in terrestrial plants for rhizome branching (Molenaar et al. (2000)), using temperature to stimulate only above-ground biomass growth (Zupo et al. (1997)), or considering growth in other plant compartments (leaves, rhizomes, and epiphytes) by incorporating light and nutrient availability (Elkalay et al. (2003)). In this context, RENOVATE project (Marcelli et al. (2023)), adopts an ecosystem-based approach to compensate for and mitigate anthropogenic impacts in the Sites of Community Importance (SCI) near Civitavecchia port in the northeastern Tyrrhenian Sea. Using a model-based approach, it focuses on restoring ecosystem services provided by marine benthic habitats, such as *P. oceanica* and coralligenous substrates, to enhance coastal resilience against extreme wave events. It should be emphasized, however, that this resilience

enhancement is understood to apply primarily to moderate storm conditions and chronic erosion processes, rather than to extreme cyclonic or hurricane-equivalent events, under which seagrass meadows themselves face substantial risk of mechanical failure and eradication. The lack of specific management plans for SCIs, such as ecofriendly buoys to prevent anchoring of recreational boats on *P. oceanica* meadows, anti-trawling barriers to deter fishing boats from using nets within SCIs, and an early warning system for dredging and accidental hydrocarbon spills, renders *P. oceanica* vulnerable to various anthropogenic stressors present in the area. Urban and industrial discharges from aquaculture and power plants, the presence of an oil platform, trawling activities, and harbour activities connected to Civitavecchia port have significantly impacted the health of the meadows.

3.1.3 The present study approach

This research employs a numerical modelling framework to quantify the wave-attenuation effects of flexibility and seasonal dynamics of *P. oceanica* under typical and moderate wave conditions, with the aim of enhancing the accuracy of coastal zone simulations and understanding the role of vegetation in modulating nearshore hydrodynamics. Through targeted data collection, we enrich our modelling framework with: (i) a detailed characterization of the phenotypic traits based on substrate types in which the seagrass thrives, and (ii) incorporation of seasonal variability in canopy height, by estimating and imposing annual growth and fall of *P. oceanica* leaves. We attempt to validate a numerical model's response using high-resolution local vegetation data, addressing the need to incorporate temporal variability in seagrass biomechanics. As shown by Vettori et al. (2021), seasonal changes and nutrient availability over the year influence blade size, rigidity, and buoyancy, affecting seagrass interactions with hydrodynamic forces. Integrating this information into wave model could enhance the accuracy of simulations in wave-dominated environments, although such data are frequently limited or lacking.

The remainder of this study is structured as follows. Section 3.2 outlines the modelling framework and its implementation, followed by the model validation using a case study from Cala Millor. The symbols and their corresponding units of measurement used in this study are provided in Table 3.2.1. Section 3.4 presents a case study in the Civitavecchia coastal strip, where advancements in modelling plant flexibility and seasonal effects are tested throughout the seasonal cycle using a high-resolution domain of up to 20 meters over the vegetated canopies. The main results of these advancements are then presented in Section 3.5, including the wave model performance analysis using wave buoy data and the investigation of wave attenuation induced by seagrass meadows over the SCIs. The key findings 3.6 are then reported in the final section of the chapter. Further possible improvements and limitations of the model are also discussed.

3.2 Modelling framework

The core model utilized in this study is WW3 (WW3DG, 2019) model, which solves the action density balance equation for the direction and wave number spectrum (Eq. 3.2.1).

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{\mathbf{x}}N + \frac{\partial}{\partial k} \dot{k}N + \frac{\partial}{\partial \theta} \dot{\theta}N = \frac{S}{\sigma} \quad (3.2.1)$$

The wave action is a function of the energy spectrum, $F(k, \theta, t, x)$, and intrinsic frequency, σ . x is a two-dimensional space, either in Cartesian, or spherical coordinates, over which the wave action is advected at group velocity relative to the mean current, $\dot{\mathbf{x}} = c_g + U$, with the rate of change in spectral space, $\dot{k}$ and $\dot{\theta}$.

WW3 has been used worldwide from global (Sharmar et al. (2021); Mentaschi et al. (2020)) to regional (Causio et al. (2021); Causio et al. (2024)) and coastal applications in both standalone, as in the present work, and coupled modes (Clementi et al. (2017); Causio et al. (2025)). The modified version of WW3 implemented by Pillai et al. (2022b), who incorporated the dissipation source term due to rigid vegetation, served as the foundation for the further advancements

Table 3.2.1. List of symbols used in Section 3 and their corresponding units of measurement.

Symbol	Description	Units of measure
g	Gravitational acceleration	LT^{-2}
U_b	Near-bed wave orbital velocity	LT^{-1}
H_s	Significant wave height	L
$\tilde{C}_D$	Drag coefficient	-
h	Water depth	L
l_v	Leaf length	L
l_e	Effective leaf length	L
b_v	Stem width	L
N_v	Vegetation (shoot) density	L^{-2}
t_v	Vegetation thickness	L
ρ_v	Tissue density	ML^{-3}
ρ	Water density	ML^{-3}
$\tilde{k}$	Average wavenumber	L^{-1}
k	Wavenumber	L^{-1}
λ	Wavelength	L
$\tilde{\sigma}$	Average wave frequency	T^{-1}
σ	Wave frequency	T^{-1}
θ	Wave direction	-
T_{peak}	Peak wave period	T
c_g	Group velocity	LT^{-1}
U	Ambient current	LT^{-1}
$\dot{\mathbf{x}}$	Combined advection velocity	LT^{-1}
∇	Differential operator in 2-d space	L^{-1}
$\dot{\theta}$	Propagation velocity in spectral wave direction space	T^{-1}
$\dot{k}$	Propagation velocity in spectral wavenumber space	$L^{-1}T^{-1}$
S_{bot}	Dissipation term due to bottom friction	L^3T^{-2}
$S_{ds,veg}$	Dissipation term due to vegetation	L^3T^{-2}
N	Action density	L^2T^{-1}
E_{tot}	Total energy	L^2
$E(\sigma, \theta)$	Spectral energy density	L^2
E	Elastic modulus	$ML^{-1}T^{-2}$
Γ	Empirical constant	L^2T^{-3}
n	Ratio of phase velocity to group velocity	-
I	Second moment of area	L^4
B	Buoyancy parameter	-
Ca	Cauchy number	-

in this work. To better model the intricate dynamics of the coastal region at finer resolutions and complex geometry, an unstructured grid configuration was employed.

The vegetation term is incorporated into the model by augmenting the bottom dissipation source term, S_{bot} , given by a simple empirical linear JONSWAP parametrization (Hasselmann et al. (1973)), as defined in Eq. 3.2.2.

$$S_{bot}(k, \theta) = 2\Gamma \frac{n-0.5}{gh} N(k, \theta) + S_{ds,veg} \quad (3.2.2)$$

The simplest approach to account for vegetation wave damping effect in a wave model is the equation proposed by Dalrymple et al. (1984) and Mendez and Losada (2004) and adapted in a spectral form by Suzuki et al. (2012) (Eq. 3.2.3).

$$S_{ds,veg} = -\sqrt{\frac{2}{\pi}} g^2 \tilde{C}_D b_v N_v \left(\frac{\tilde{k}}{\tilde{\sigma}} \right)^3 \frac{\sinh^3(\tilde{k}l_v) + 3\sinh(\tilde{k}l_v)}{3k \cosh^3(\tilde{k}h)} \sqrt{E_{tot}} E(\sigma, \theta) \quad (3.2.3)$$

This formulation models vegetation as rigid leaves and has been utilized in a number of studies (Gupta et al. (2020), Pillai et al. (2022b), Abdolali et al. (2022), Jacob et al. (2023)). Several alternative formulations have been proposed to address the overestimation of wave damping, some of which incorporate the Reynolds number or Keulegan-Carpenter number, as recently described by Abdolali et al. (2022), while others are based on plant bending. Our study adopts the latter, specifically by implementing the formulation proposed by Luhar and Nepf (2011) (Eq. 3.2.4) and further refined by Luhar and Nepf (2016) and Lei and Nepf (2019), in which the effective leaf length, l_e , scales with the blade length to the wave excursion (A_w) ratio, L (Eqs. 3.2.5, 3.2.6). In this approach, the effect of blade flexibility is incorporated into the source term computation by replacing the actual leaf length, l_v , with l_e . While the original formulation was developed for unidirectional flow conditions, we formulate the Cauchy number, Ca , as a function of the wave bottom orbital velocity, U_b , to account for the wave-induced oscillatory flows. These modifications were proposed by Luhar and Nepf (2016) using the oscillatory velocity scale as a function of the wave orbital excursion, and later adopted by Beth Schaefer and

Nepf (2022) and Vettori et al. (2024).

$$l_e = l_v - \frac{1 - 0.9Ca^{-1/3}}{1 + Ca^{-3/2}(8 + B^{3/2})} l_v \quad (3.2.4)$$

$$\frac{l_e}{l_v} \sim Ca^{-1/3} \quad \text{for } L \ll 1 \quad (3.2.5)$$

$$\frac{l_e}{l_v} \sim (Ca \cdot L)^{-1/4} \quad \text{for } L \gg 1 \quad (3.2.6)$$

$$\begin{aligned} \text{where } B &= \frac{(\rho - \rho_v) g b_v t_v l_v^3}{EI}, \\ Ca &= 0.5 \frac{\rho C_D b_v U_b^2 l_v^3}{EI}, \\ I &= \frac{b_v t_v^3}{12}, \\ L &= \frac{l_v}{A_w} \end{aligned}$$

3.3 Model validation

Table 3.3.1. Numerical model parameters used for Infantes et al. (2012) case study.

Bathymetry	Derived from Infantes et al. (2012)
Plants	<i>P. oceanica</i>
Leaf length l_v	80 cm
Shoot density N_v	615 m ⁻²
Elastic modulus E	0.47 GPa
Thickness t_v	0.0003 m
Tissue density ρ_v	900 kg m ⁻³
Leaf width b_v	0.0092 m
Simulation period	2009/07/12 - 2009/07/20
Forcing	Wave energy spectrum at the open boundary from Infantes et al. (2012). No winds.
Initial conditions	At rest

To validate the bottom vegetation effects described in Eqs. 3.2.3, we developed a model validation case based on the study by Infantes et al. (2012). This study represents a crucial benchmark as it involved a measurement campaign of wave heights over *P. oceanica* meadows in the Balearic Islands. Additionally, they provided fundamental data on beach depth profiles, *P. oceanica* parameters (i.e. shoot density, leave length, meadow extensions), and wave height attenuation along a transect. Our validation methodology aimed to replicate the conditions described in Infantes et al. (2012) within our numerical model implementation. The numerical setup is summarized in Table 3.3.1.

The domain of Cala Millor (Figure 3.3.1) was reconstructed using an unstructured mesh with a horizontal resolution of approximately 20 meters, extending 1.2 km radially from the shore and 0.7 km along the coastline. The extent and coverage of the vegetation meadows were chosen to reflect the real domain investigated in Infantes et al. (2012), preserving the locations of the moorings, distances from the coast, and distances between moorings. The depth profile and simulation time window were derived from the original work. To minimize uncertainty from external forcing and to investigate vegetation-induced wave dissipation more accurately, we excluded wind forcing from the simulation. Only the measured wave height time series at the offshore mooring location was imposed at the open lateral boundary (indicated in red in Figure 3.3.1) of the domain. This boundary forcing represented the only input for our validation case study. The wave direction was assumed to be perpendicular to the coastline.

We conducted three numerical experiments with the following configurations: (i) no vegetation (*no_veg*), using the default code of WW3; (ii) rigid vegetation (*veg_rigid*), including the implementation used in Pillai et al. (2022b); (iii) flexible vegetation (*veg_flex*), including the formulation proposed in this study. The assessment of wave attenuation was carried out by comparing the simulation results with wave measurements taken by Infantes et al. (2012) at a nearshore buoy after the waves traveled approximately 1 km over the vegetation.

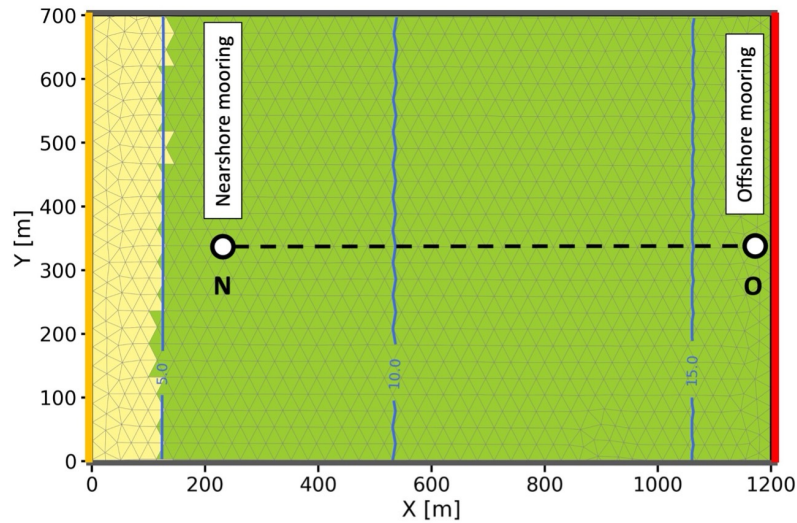


Figure 3.3.1. A Cala Millor case study domain and bathymetry customized from Infantes et al. (2012), with location of mooring data. *O* denotes offshore moorings, while *N* denotes nearshore moorings. Green mesh elements indicate elements with vegetation, while yellow elements do not include vegetation at the bottom. The dashed line represents the transect *N-O* analyzed later.

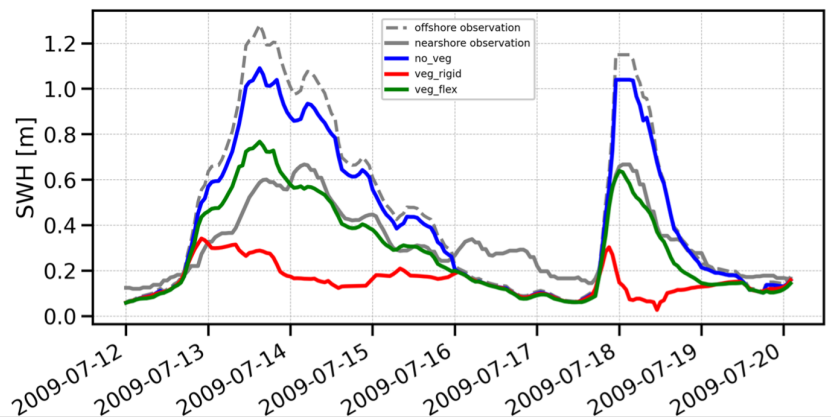


Figure 3.3.2. Significant wave height (SWH) timeseries comparison for *no_veg* (no vegetation), *veg_rigid* (rigid vegetation) and *veg_flex* (flexible vegetation) experiments against nearshore and offshore moorings in Figure 3.3.1.

Figure 3.3.2 presents the results of the test case validation for the period investigated by Infantes et al. (2012). According to the observations, the reduction in significant wave height H_s (SWH), considering the combined effects of vegetation and depth-induced damping, is approximately 50-60% over a distance of ~ 1 km.

The three colored lines represent our numerical experiments. As expected, the *no_veg* experiment (blue line) closely mirrors the offshore wave height, as it only accounts for depth-induced dissipation. This low dissipation from offshore to nearshore can be approximately quantified as 10-20% under the simulation conditions. In contrast, the *veg_rigid* experiment (red line) demonstrated the most significant wave damping, showing minimal variability in wave height throughout the simulation period. It exhibited a substantial wave reduction of $\sim 80\%$, with a computed bias of -0.18 m and an RMSE of 0.178 m. The *veg_flex* experiment (green line) achieved the highest accuracy, with a dissipation of $\sim 40\text{-}50\%$, closely matching the observations and aligning well with the data, yielding a bias of -0.04 m and an RMSE of 0.126 m.

Figure 3.3.3 presents a map (a) and transect profile (b) of SWH, illustrating wave attenuation during the peak event on 07/17 at 23:00. The offshore observation recorded a wave height of 1.2 m, which corresponds to a modeled mean period of 5.25 s (IQR: 4.5–5.8 s). At the nearshore station, SWH decreased to 0.65 m, representing 50% wave dissipation due to the combined effects of vegetation and shoaling. This high attenuation is physically consistent with the short-period nature of the event; as shown in Eq. 3.2.3, the dissipation term acts as a low-pass filter that preferentially attenuates shorter-period energy. This pattern is accurately captured by the *veg_flex* simulation, confirming that attenuation effects are amplified under increased wave height and steeper wave conditions, consistent with Eqs. 3.2.3 and 3.2.4.

It is noteworthy that the SWH slopes in the N-O transect of Figure 3.3.3b exhibits varying degrees of reduction in the different cases. The *no_veg* simulation showed almost a SWH linear decrease with a very low slope leading to a significant overestimation of SWH. The rigid vegetation simulation (*veg_rigid*) curve shows a linear and rapid drop in SWH as the wave prop-

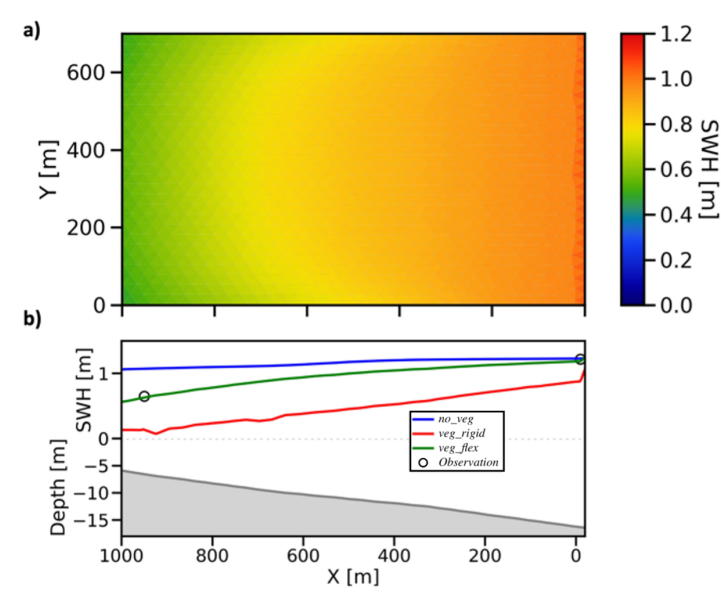


Figure 3.3.3. (a) Map of SWH for *veg_flex* configuration and (b) SWH profiles for the three configurations (*no_veg*, *veg_rigid* and *veg_flex*) along the transect N-O (as indicated in Figure 3.3.1) at the event peak of 2009-07-17 - 23:00.

agates from the boundary over the seagrass meadows. In contrast, the *veg_flex* implementation displays non-linearity as waves approach the shore. This behavior is driven by flow-induced reconfiguration, as waves shoal and energy density increases, the higher hydrodynamic drag forces cause the blades to bend, reducing the effective vegetation length. This reduction in the vertical canopy profile creates a non-linear relationship between wave height and energy dissipation, as the plants streamline in response to increasing Cauchy number. Consequently, the disparity between *no_veg* and *veg_flex* simulations grows non-proportionally as the wave height increases.

Given the high accuracy demonstrated by the flexible vegetation simulation set-up, this model structure is further used in the coastal area of Civitavecchia along the Latium coast of the Tyrrhenian Sea.

3.4 The Civitavecchia case study

To assess the impact of *P. oceanica* meadows on wave attenuation throughout the seasonal cycle, the model was implemented in the coastal area of the northeastern Tyrrhenian Sea, Italy, extending from Tarquinia in the north to S. Severa in the south, with Civitavecchia in central zone of the domain (Figure 3.4.1).

The study area contains four SCIs established by the European Union's Habitat Directive (92/43/CEE) under Annex 1. Moving from north to south, the SCI 6000004 ("Seabeds between Marina di Tarquinia and Punta delle Quaglie"), SCI 6000005 ("Seabeds between Punta S. Agostino and Punta Mattonara"), SCI 6000006 ("Seabeds between Punta del Pecoraro and Capo Linaro"), and SCI 6000007 ("Seabeds off Santa Marinella") are present, hereinafter referenced as SCI 1, SCI 2, SCI 3, and SCI 4 respectively (Figure 3.4.1a).

In this area, the *P. oceanica* meadows exhibit a discontinuous distribution and high variability in structural and functional descriptors (Figure 3.4.1a), reflecting the heterogeneity of the local environments and the presence of various socio-economic activities (Gnisci et al. (2020), Bonamano et al. (2021)). The upper depth limit of *P. oceanica* meadows was determined using high-resolution remote sensing imagery (Borfecchia et al. (2019)), while in the shallower depths acoustic surveys (Ardizzone et al. (2018)) have been used. *P. oceanica* occur at depths ranging from 0.5 m to 25 m and are situated on rocky substrates (depicted by the red area in Figure 3.4.1a on the right), degraded matte, indicating sediment-rich areas with reduced plant cover and dead matte with isolated patches of *P. oceanica*, (the violet area in Figure 3.4.1a on the right), and sandy bottoms (the green area in Figure 3.4.1a on the right). These meadows exhibit high fragmentation and display significant variability in coverage, ranging from 6% to 98%, with a coefficient of variation of 72.4% (Gnisci et al. (2020)). Moreover, the density is influenced by the meadows' architecture, with an average of 141.7 ± 62.9 shoots m^{-2} (Bonamano et al. (2015); Gnisci et al. (2020)).

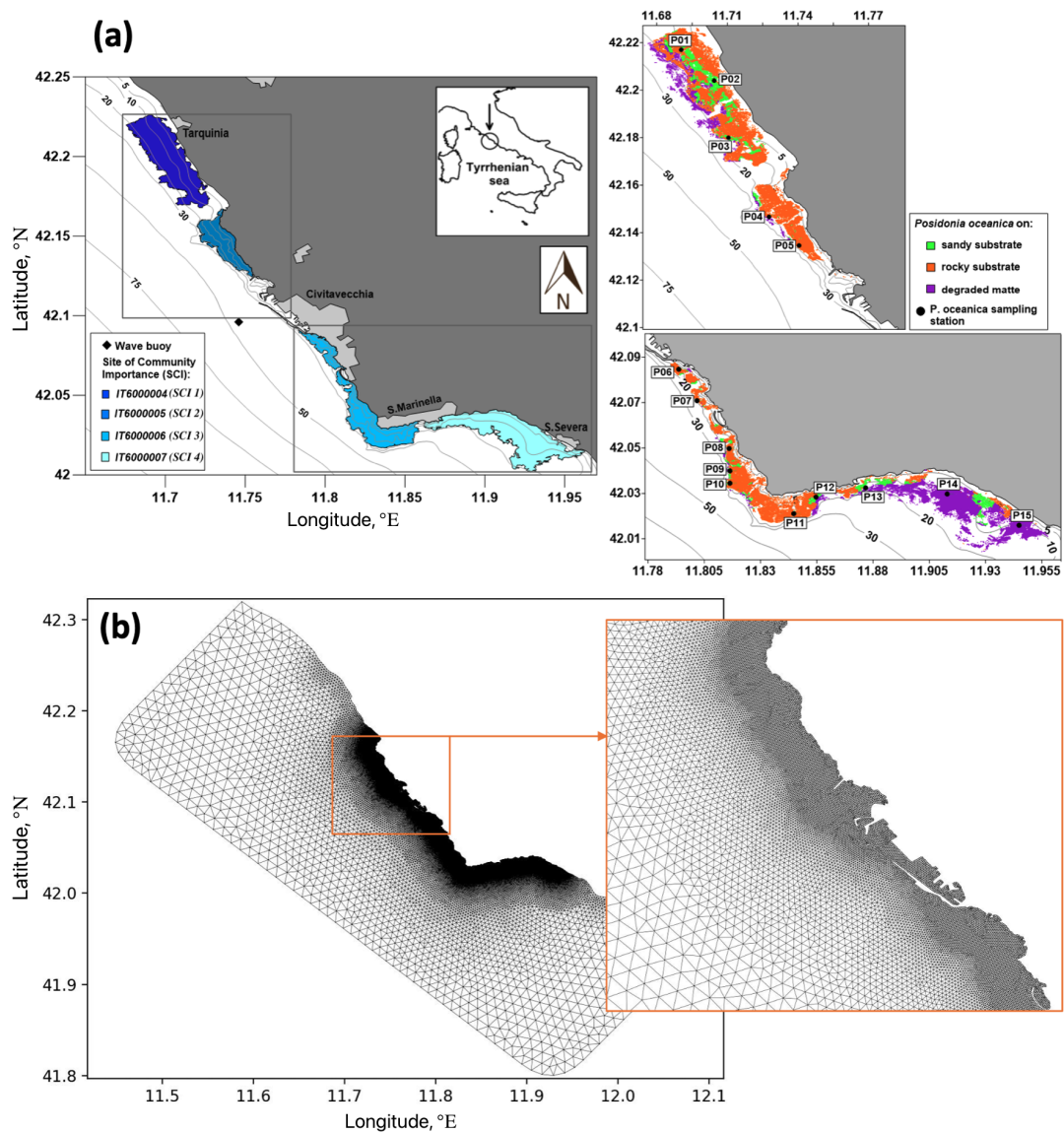


Figure 3.4.1. Map of the area of Civitavecchia with bathymetry, Sites of Community Importance (SCI), observations used in the study and distribution of the *P. oceanica* over the different substrate types (*P. oceanica* on rock, *P. oceanica* on sand and matte, and degraded matte with *P. oceanica*). (b) Mesh of the computational domain with enlarged views in the vicinity of the Civitavecchia harbour.

3.4.1 Model setup

Spanning approximately 90 km along the northeastern Tyrrhenian Sea coast, the model domain (Figure 3.4.1b) is centered around the port of Civitavecchia. Coastline reconstruction involved integrating data from recent high-resolution satellite images with the OpenStreetMap dataset (Haklay and Weber (2008)). Advanced, customized meshing tools were employed to achieve a high grid resolution of around 20 m near the shore and a coarser resolution of approximately 2 km offshore. GMSH (Geuzaine and Remacle (2009)) was utilized for mesh generation, while BLENDER (Blender Community (1994)) facilitated optimization and quality checks of the triangles (Bonamano et al. (2024)). The meshing algorithm, based on a frontal Delaunay approach (Remacle et al. (2013)), defines the nominal grid size as the maximum edge length of the triangles.

Bathymetric data were obtained from the EMODNET product (Consortium (2016)) at a resolution of $1/8 \times 1/8$ arc-min (approximately 230×230 m) for the open sea. This data was augmented with high-resolution multi-beam data collected in specific coastal areas, including near the harbour area and within the SCIs, provided by the Autorità di Sistema Portuale del Mar Tirreno Centro Settentrionale. At the open lateral boundaries, the domain is forced with the downscaled Copernicus regional model (Korres et al. (2023a)) mean wave parameters (H_s , θ , T_{peak}) of 1h frequency for the period of simulation of 1 year (2016/10/01 - 2017/09/30). ECMWF operational analysis (Owens and Hewson (2018)) were used for wind data at 6h frequency.

Numerical propagation for the unstructured triangular grid was set to CRD-N-scheme (Ricchiuto et al. (2005)) and the spectral propagation part is solved with simple implicit 1st order upwind schemes. The linear input source term was activated for initial wave growth and consistent model spin-up, as described by Cavaleri and Rizzoli (1981), with the filter function to limit the effect of low-frequency energies at initial growth (Tolman (1992)). Sink terms due to negative wind input, whitecapping dissipation, and wave-turbulence interactions, as defined

Table 3.4.1. Description of the numerical experiments.

Experiment	Configuration	Description
NV	No vegetation	The simulation is conducted without any vegetation present.
VF	Flexible vegetation with varying substrates	The simulation incorporates flexible vegetation with annual mean leaf length values for <i>P. oceanica</i> (l_{av} as shown in Table 3.4.2). Spatial variations in leaf length and shoot density are accounted for based on substrate types (rock, sand, and degraded matte).
VFS	Flexible vegetation with varying substrates and seasonal growth factors	This simulation captures the seasonal growth of <i>P. oceanica</i> , as depicted in Figure 3.4.2. Initial values (l_v) for October 2016 are provided in Table 3.4.2. Growth and shoot density vary across substrate types (rock, sand, and degraded matte).

by Ardhuin et al. (2009), were also included. Nonlinear wave-wave interactions were modelled using the Discrete Interaction Approximation (DIA) (Hasselmann and Hasselmann (1985). For the bottom friction the simple linear JONSWAP parametrization derived by Hasselmann et al. (1973) was used. As a function of bottom topography, waves exceeding a threshold height, determined by a statistical description of surf-zone wave heights, were set to break and dissipate energy following the approach of Battjes and Janssen (1978). Triad nonlinear interactions were resolved using the LTA model of Eldeberky and Battjes (1996). Wind stresses were computed according to Donelan et al. (2012), while the wind field was interpolated linearly in time and space. Shoreline reflection was activated. Flexible vegetation was incorporated into the bottom friction definition, also introducing the seasonal variations where leaves undergo growth and regression, with elongation during favorable conditions and shortening due to natural senescence and environmental factors as shown in Figure 3.4.2. The initial leaf parameters were encoded, and a mask file was used to mark vegetation distribution and a substrate type at each location.

Table 3.4.2. Vegetation parameters for different substrates of *P. oceanica* meadows with initial and averaged over the simulation period (annual mean) leaf length values, derived from field sampling within the study area.

<i>P. oceanica</i> parameters	Rock	Sand and Matte	Degraded Matte
$N_v \text{ (m}^{-2}\text{)}$	209.46	277.57	145.3
$l_v \text{ (cm)}$	47.5	46.3	41.2
$l_{av} \text{ (cm)}$	28.5	35.8	25.5
$b_v \text{ (cm)}$	0.92	0.92	0.92
$t_v \text{ (cm)}$	0.03	0.03	0.03
$\rho_v \text{ (kg/m}^2\text{)}$	218.6	218.6	218.6
$E \text{ (GPa)}$	0.47	0.47	0.47

To assess the wave attenuation in the study area, we conduct three experiments with different parametrizations in the vegetation module (Table 3.4.1). In the first configuration, we simulated the absence of the meadows in the study area by excluding the source term $S_{ds,veg}$. In the second configuration, VF, all the parameters of the vegetation module remain constant over time, while leaf length and shoot density vary according to different substrate types given in Table 3.4.2. The values for leaf length and shoot density represent the annual averages derived from inter-annual sampling (see Section 3.4.2). The elastic modulus value is set at 0.47 GPa and was determined by Folkard (2005), who measured the angle of deflection of a small, cantilevered strip of the sheeting when loaded with small weights. In the third configuration, VFS, the model mimics the seasonal variations in canopy height, defined as the maximum length of a leaf within a shoot. This is achieved by fitting a fifth-degree polynomial curve (Eq. 3.4.1) to canopy height data collected in *P. oceanica* meadows within the study area, with the coefficients provided in Table 3.4.3.

$$l = l_v + \alpha_1 \cdot t + \alpha_2 \cdot t^2 + \alpha_3 \cdot t^3 + \alpha_4 \cdot t^4 + \alpha_5 \cdot t^5 \quad (3.4.1)$$

where l_v represents the initial leaf length at the start of the simulation in October, t denotes the day of the year, and l is the adjusted leaf length, accounting for seasonal variations. The initial leaf length values for October 2016 are listed in Table 3.4.2.

Table 3.4.3. Growth curves coefficients for the considered *P. oceanica* traits in the study.

Curves substrates	α_1	α_2	α_3	α_4	α_5	l_v
rock	-1.61	2.39×10^{-2}	-1.55×10^{-4}	4.71×10^{-7}	-5.25×10^{-10}	47.51
sand	-7.43	9.50×10^{-3}	-7.11×10^{-5}	2.65×10^{-7}	-3.45×10^{-10}	46.30
degraded matte	-1.98	3.33×10^{-2}	-2.26×10^{-4}	6.82×10^{-7}	-7.43×10^{-10}	41.23

The growth curves obtained for the three substrate types in Figure 3.4.2 exhibit a trend similar to those described by Ott (1980) in Gulf of Naples, an area in the Tyrrhenian Sea close to the current study area with similar wave climate. A similar approach has already been employed in previous studies to analyze the annual growth dynamics of *P. oceanica* (Duarte (1989); Alcoverro et al. (1995)) and to estimate the carbon dioxide fixed by the plants (Vassallo et al. (2013)).

According to the growth patterns, maximum leaf development in *P. oceanica* occurs toward the end of the summer season. This is followed by the onset of intense autumnal storms, which induce the detachment of senescent leaves, leading to a marked decline in canopy height during winter. At this stage, only juvenile shoots persist, characterized by their minimum annual leaf length. Notably, the timing of minimum canopy height varies with substrate type, a pattern that may reflect both biological variability and senescence cycles, as well as observational uncertainty during winter months, when adverse weather conditions hindered data collection due to the infeasibility of scuba diving.

Specifically, in the study area, *P. oceanica* growing on sandy and matte substrates exhibits faster growth and greater leaf elongation during summer months. On a sandy substrate, which facilitates root penetration (Di Maida et al. (2013)), meadows demonstrate greater resilience

by postponing the onset of senescence and maintaining a higher minimum canopy height during winter. In contrast, rocky substrate imposes mechanical limitations on root penetration, restricting *P. oceanica* to establishing within crevices (Hemminga and Duarte (2000)), reflecting a greater demand for anchorage and the reduced nutrient availability (Giovannetti et al. (2008)). Given that sediment-based nutrient uptake through the roots is a primary pathway for this species (Touchette and Burkholder (2000)), these constraints likely contribute to diminished growth performance in winter months. Similarly, canopy height is lower for *P. oceanica* growing on degraded matte, as the reduced shoot density offers limited protection against intense storms, which tend to uproot nearly all leaves, leaving only those a few millimeters long. Thus, the values shown in Table 3.4.2 for initial leaf length reflect initial conditions of *P. oceanica* meadows in October and are subject to change over the simulation according to Figure 3.4.2 for VFS experiment.

The growth factor is inherently site-specific, influenced by physical and environmental variables such as wave action, turbidity, temperature, proximity to river mouths, and nutrient availability, requiring localized data collection. Unlike biogeochemical models, the proposed formulation, based on in situ observations, does not rely on abiotic parameters, which are often limited by poor temporal coverage (e.g., cloud-obstructed satellite data) or insufficient spatial resolution in coastal zones (e.g., the 4 km grid used by CMEMS regional models).

3.4.2 Observational data

To model the *P. oceanica* meadows in the four SCIs, structural, morphological, and dynamic parameters of the seagrass were collected at 15 stations (POS1-POS15) in 2017, as illustrated in Figure 3.4.1a on the right. The sampling of plants followed a hierarchical design in accordance with the standard protocol reported in Buia et al. (2004). By scuba diving, shoot density, N_v , was determined as shoots per square meter by counting the number of shoots within nine randomly selected squares (40×40 cm). A total of 18 orthotropic rhizomes were randomly

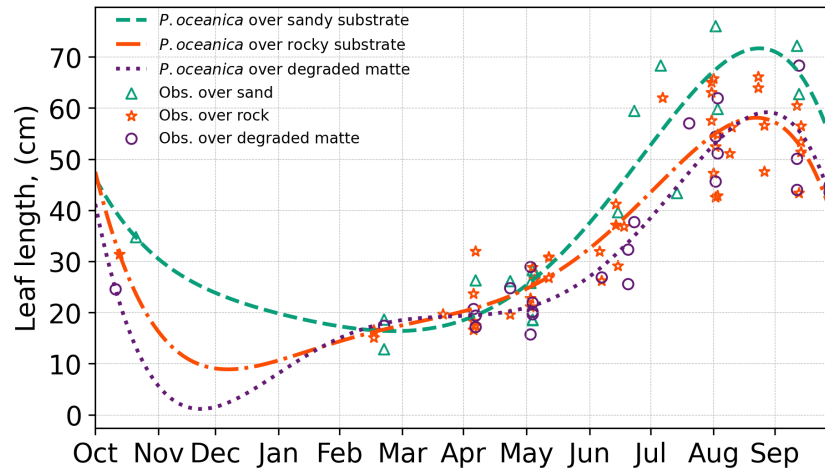


Figure 3.4.2. *P. oceanica* leaf length variation throughout the year, showing seasonal observations alongside fitted growth curves.

collected from each station (six rhizomes for three replicates per station) for phenological analysis (Giraud et al. (1979)). In the laboratory, leaves of *P. oceanica* were scraped to remove epiphytes and then washed in distilled water. Subsequently, biometric variables such as the number, length (l_v), width (b_v), and thickness (t_v) of juvenile, intermediate, and adult leaves per shoot were measured at each station, following Giraud's classification (Giraud (1977)). According to Pergent-Martini et al. (2021), the longest leaf within a shoot is most often the third-ranked leaf, which has therefore been adopted as the representative value for canopy height. To calculate the tissue density of the leaves (ρ_v), the oldest leaf with an intact apex was dried in an oven at 60°C for 48 hours and then weighed. Leaf density was then estimated by dividing the dry weight of the leaf by its volume, calculated from the previously defined biometric data.

To validate the WW3 model, wave data were gathered from the wave buoy of the Civitavecchia Coastal Environment Monitoring System (C-CEMS), developed by the Laboratory of Experimental Oceanology and Marine Ecology and operational since 2005 in the coastal marine area of Civitavecchia (Bonamano et al. (2016); Bonamano et al. (2021); Bonamano

et al. (2023)). The Datawell wave buoy is equipped with a wave motion sensor mounted on a stabilized platform, along with accelerometers and a magnetic compass. It has enabled the measurement of wave height (with an accuracy of 0.5% of the measured value), wave direction, wave period at a depth of approximately 50 meters. The simulations were validated using SWH measurements recorded from October 2016 to November 2017.

3.5 Findings and interpretation

In this section, we first analyze the wave fields over the Civitavecchia region (Section 3.5.1) based on VFS configuration results and discuss the overarching wave patterns. Subsequently, in Section 3.5.2, we validate the VFS experiment output against observational data, evaluating the performance metrics such as correlation coefficient and bias. In Section 3.5.3 we intercompare the VF and VFS experiments against the NV.

3.5.1 Wave field analysis

The area of Civitavecchia is influenced by the waves approaching predominantly from southwest as shown on an annual mean SWH, Figure 3.5.1 (a, b). In VFS configuration, the waves are impacted by the vegetated zones producing irregular SWH patterns along the coast. The deep blue colour depicts the harbour zone, which is shielded by the breakwater. The patches of light blue regions, in (a), show the annual mean wave height reduction due to the presence of vegetation down to 0.2 m from 0.4 m in NV configuration, (b). The seasonal SWH maps (Figure 3.5.1 c, d, e, f) illustrate that waves are greater during autumn to winter period (OND, JFM), with offshore waves averaging 0.8 m and diminishing to 0.4 m at the coast of Civitavecchia. During this period, the predominant wave direction is northward, highlighting the exposure of site SCI 3 to substantial wave activity at the Santa Marinella coastal edge. Conversely, during the warmer spring to summer period (AMJ, JAS), wave energies decrease by $\sim 40\%$, with off-

shore waves averaging 0.5 m and reducing to 0.3 m at the coast. During this period, the waves approach the coast more perpendicularly and SCI 4 benefits from the partial protection provided by the Santa Marinella headland, resulting in wave divergence.

3.5.2 Model performance analysis

We assess the wave model's performance using offshore buoy data described in Section 3.4.2. However, since the buoy is located outside the vegetated area and beyond its influence, the validation does not account for the effects of seasonal variability or flexibility in the model implementation. Nevertheless, the SWH timeseries in Figure 3.5.2a at the wave buoy location (see Figure 3.4.1a) provides valuable insight into high-amplitude waves over the simulated period, with wave heights reaching 4 meters, peaking in March. These strong wave events occur more frequently during colder seasons. As previously noted, we anticipate that high-amplitude waves in autumn will impact the coastline and significantly damage the vegetation canopies starting over the seasonal cycle in October, as observed in Figure 3.5.2a. The figure compares the VFS experiment results with wave observations collected during the same period, represented in red. To minimize the impact of localized point-wise variations, the average values from the five nodes closest to the buoy were used. The model generally overestimates wave heights during autumn and winter, while slightly underestimating peak wave events in spring and summer. When wave heights are below 0.5 m, the model tends to provide lower estimates than observed. Overall, the model demonstrates strong performance, accurately capturing peak events with a high correlation coefficient of 0.95 and a bias of -0.14 m (Figure 3.5.2b).

We further analyze the model performance calculating the dimensionless relative bias in SWH associated with the incoming wave direction (Figure 3.5.3). The relative bias is defined as the mean error normalized by the maximum of the root mean square or the absolute mean of the observations $\langle H_{mod} - H_{obs} \rangle / \max(\text{rms}_{H_{obs}}, |\langle H_{obs} \rangle|)$, where H_{mod} and H_{obs} represent the simulated and observed significant wave heights, respectively (Roelvink et al. (2009)). Consistent

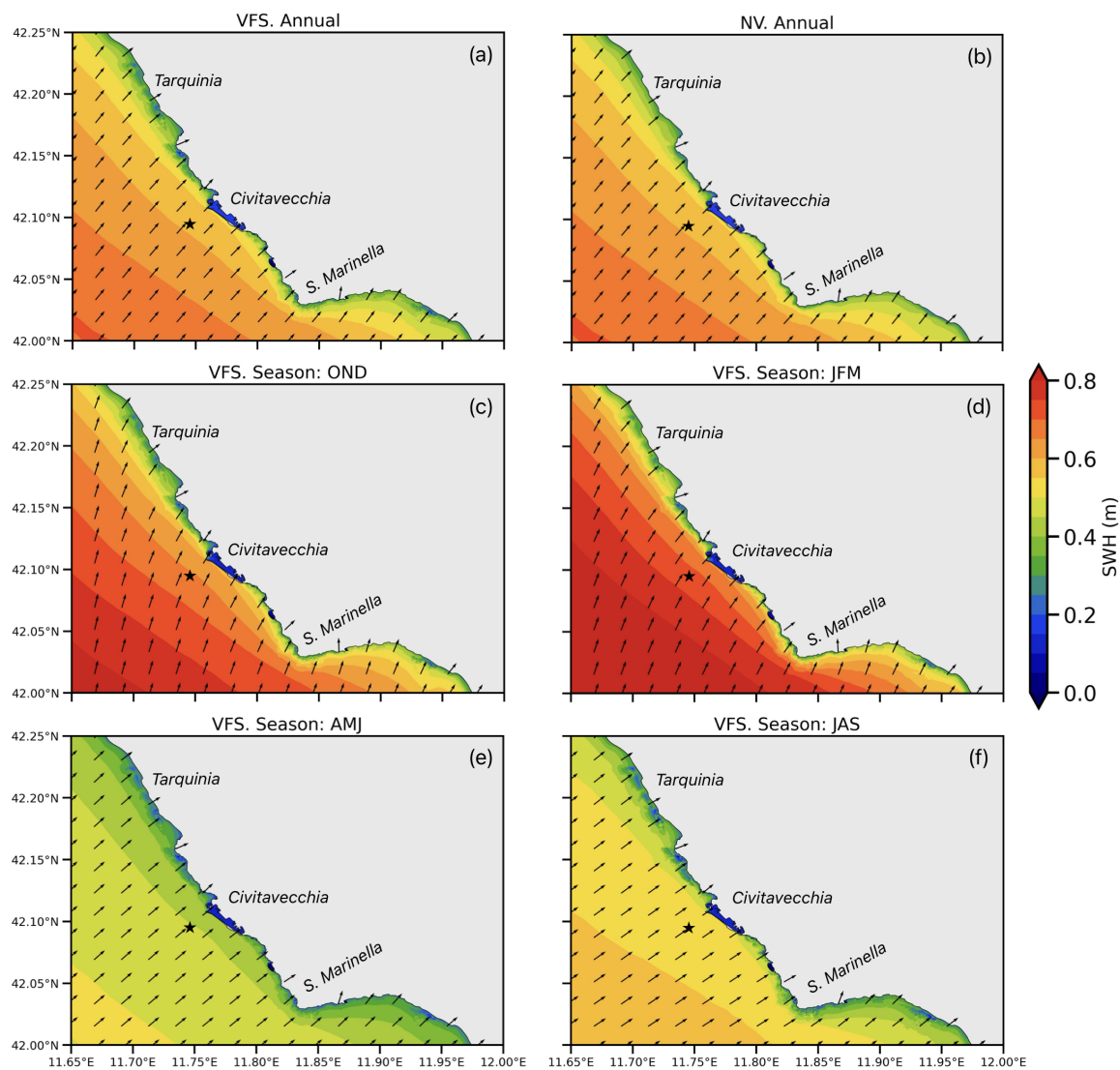


Figure 3.5.1. Maps (zoomed over the coastal area) of annual mean (a,b) of VFS and NV configurations, and seasonal (OND, JFM, AMJ, JAS) mean (c, d, e, f) SWH (1 Oct 2016 - 30 Sept 2017) including flexible vegetation and seasonality effect (VFS). The wave buoy position is indicated by the star marker.

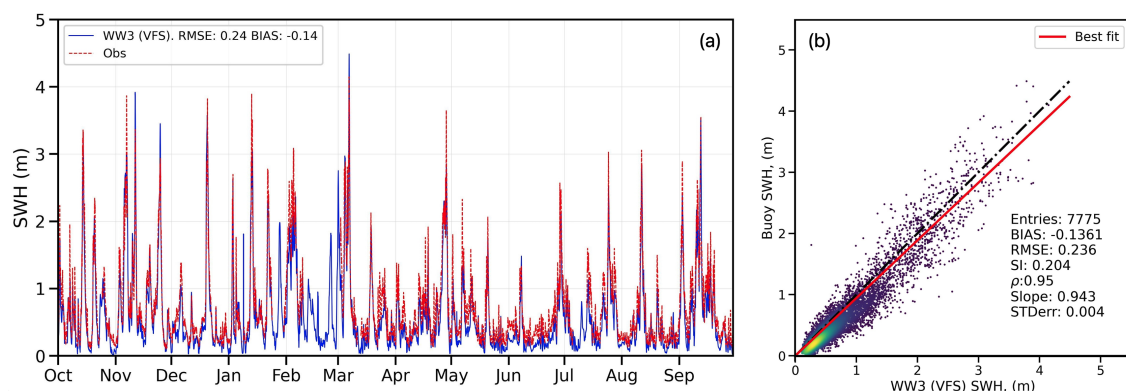


Figure 3.5.2. Comparison of the wave model results with the buoy data (Figure 3.4.1a) in terms of timeseries (a) and a scatter plot (b). In plot (b), the dash-dot black line represents the perfect correlation for the reference, while the solid red line shows the model fitting. A statistical summary is also provided.

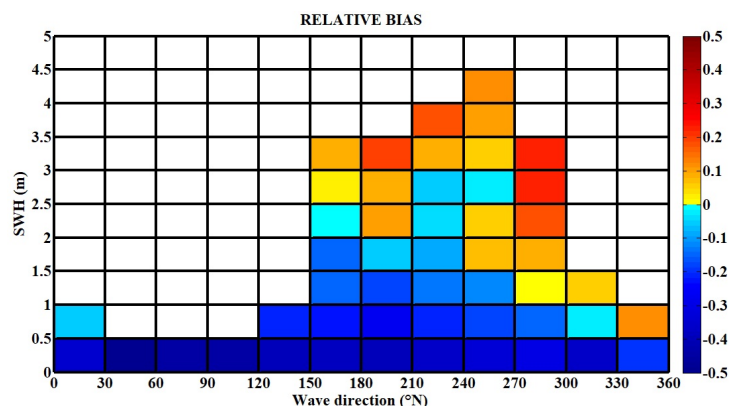


Figure 3.5.3. Heatmap of SWH and wave direction relative bias (dimensionless), with the relative bias formulation described in Roelvink et al. (2009).

with the quiver map in Figure 3.5.1a, the mean incoming wave direction is southwest, ranging between 210-240°N. We observe a 0.2 increase in SWH relative bias with rising wave height for waves ranging from 3 to 4.5 m. However, for smaller southern waves, 180°N, of 1-2 m, the model predominantly underestimates SWH, showing a negative bias of 0.3. The highest positive bias, 0.3, is most frequently observed for the western waves (270-300°N) of 2-3.5 m magnitude.

Expectedly, the lower-amplitude waves, due to their higher frequency, produce a negative bias across all directions, reaching 0.4. This effect is also evident in Figure 3.5.2a, where the model consistently underestimates SWH.

The variability in bias is likely associated with the absence of coupling effects with currents in the region. Studies identify the Bonifacio Strait as a principal driving force of cyclonic and anticyclonic gyres (Astraldi and Gasparini (1994)), forming the Bonifacio cyclone, where the winter convection is particularly strong reaching the northeastern coasts (Iacono et al. (2021)). From autumn to early spring, the northward principal stream entering the Tyrrhenian Sea from the Sardinia Channel and Sicily Strait follows along the eastern coast and splits into an outflowing stream via the Corsica Channel and a cyclonic southward flow entrained by the Bonifacio gyre (Vetrano et al. (2010)). These circulation patterns may influence wave dynamics, potentially affecting the model's performance, though the extent of this impact remains unclear and requires further investigation.

Table 3.5.1. Monthly mean H_s and U_b over vegetation area and their differences for the three experiments in Table 3.4.1.

Variable	Experiment	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
H_s (m)	VFS	0.43	0.67	0.33	0.48	0.56	0.49	0.43	0.31	0.29	0.36	0.26	0.48
	VF	0.43	0.62	0.31	0.45	0.54	0.47	0.42	0.3	0.29	0.37	0.27	0.51
	NV	0.48	0.72	0.35	0.52	0.62	0.54	0.48	0.33	0.32	0.41	0.3	0.59
H_s (%)	VFS-NV	-11.06	-7.23	-4.97	-7.16	-8.39	-10.15	-9.08	-7.53	-8.46	-12.6	-11.28	-18.36
	VF-NV	-11.25	-14.21	-10.93	-12.46	-12.76	-13.89	-10.59	-7.89	-6.91	-9.07	-7.8	-13.09
	VFS-VF	0.21	8.13	6.7	6.06	5.01	4.34	1.69	0.39	-1.66	-3.88	-3.78	-6.07
U_b (m/s)	VFS	0.08	0.14	0.07	0.09	0.12	0.1	0.08	0.05	0.04	0.06	0.04	0.1
	VF	0.08	0.13	0.06	0.09	0.11	0.09	0.08	0.05	0.04	0.07	0.04	0.1
	NV	0.09	0.16	0.07	0.1	0.14	0.12	0.09	0.06	0.05	0.08	0.05	0.13
U_b (%)	VFS-NV	-16.01	-9.41	-6.95	-10.17	-11.13	-13.36	-13.27	-13.36	-15.36	-20.07	-19.85	-24.39
	VF-NV	-16.18	-18.24	-15.37	-17.69	-16.91	-18.25	-15.45	-13.98	-12.5	-14.59	-13.84	-17.55
	VFS-VF	0.2	10.79	9.96	9.13	6.95	5.99	2.58	0.72	-3.08	-6.41	-6.97	-8.29

3.5.3 Seagrass induced wave attenuation

We compare the three experiments described in Table 3.4.1 to evaluate the contributions of flexible vegetation and seasonal effects to wave attenuation. Table 3.5.1 presents the monthly mean values of H_s and U_b , averaged across all vegetated nodes for the three experiments, along with their corresponding percentage differences. When modulated by seasonal growth patterns (VFS), the mean monthly H_s ranges from 0.2 m (JUN) to 0.6 m (NOV), with wave dissipation rates varying from a minimum of 4% in December to a maximum of 19% in September, accounting for the standard deviation of 4%. A similar seasonal variability is observed for U_b , although dissipation rates are slightly higher, ranging from 6% to 25%. In comparison, the VF experiment exhibits lower annual variability of 2% in wave attenuation, with values ranging from 7% to 14% for H_s and from 12% to 18% for U_b . Seasonality accounts for an additional 5% variability in H_s and 7% in U_b (VFS - VF), with maximum observed differences of 8% and 10%, respectively. Wave damping efficiency varies seasonally, with reduced attenuation during early stages of leaf development (NOV - DEC), when the positive difference between VFS and VF is most pronounced. Conversely, a negative difference, indicating greater attenuation under seasonal conditions, occurs between June and October, when leaf length exceeds the annual average set in the VF simulation.

The observed seasonal variability in attenuation is further influenced by the dimensionless blade length to wave orbital excursion ratio, L , according to Eqs. 3.2.5, 3.2.6, which modulates effective leaf length response to wave forcing conditions. Figure 3.5.4(a, b) depicts the maps of wave orbital excursion (A_w) with the L -ratios over the vegetated areas for VFS experiment. These maps are constructed using the annual mean, l_{avg} , and maximum, l_{max} , leaf length values, in relation to the maximum, A_w^{max} , and 90th percentile, $A_w^{90\%}$, of the wave orbital excursion. The results indicate that the condition $L \ll 1$ is primarily associated with high-energy wave events characterized by peak near-bed orbital excursions. In contrast, the $L \gg 1$ regime is more commonly encountered under typical wave conditions. The domain-averaged monthly mean

L -ratios over vegetation areas in Figure 3.5.4c illustrate that at least 65% of wave conditions fall within the $L \gg 1$ regime, scaling effective leaf length as $l_e/l_v \sim (Ca \cdot L)^{-1/4}$. Notably, this regime dominates during the summer months (June-August), a period characterized by both reduced wave orbital excursions and peak leaf lengths.

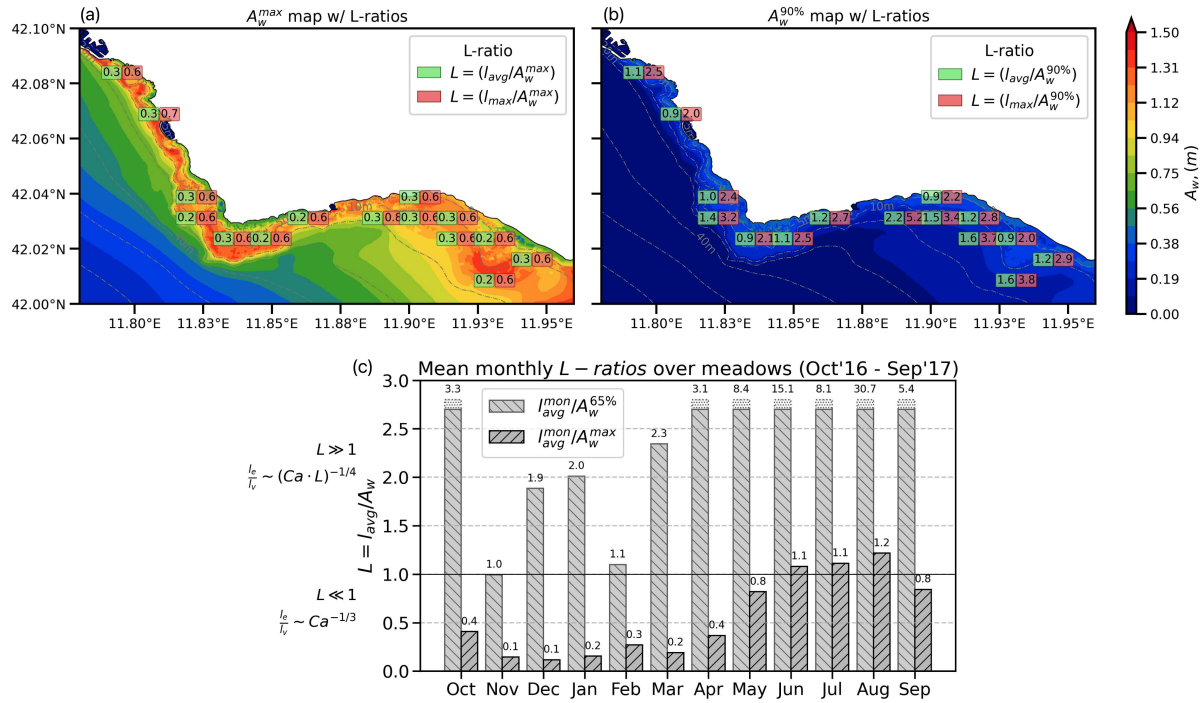


Figure 3.5.4. Maps (a, b) of wave orbital excursion (A_w) with the L -ratios over the vegetated areas; (c) the domain-averaged (over vegetation only) monthly mean L -ratios.

However, this comparison does not fully capture the impact of *P. oceanica* meadows across different substrates on wave dissipation and their temporal patterns. Therefore, we further investigate the substrate-specific and spatial (node-wise) effects of the canopy on wave behavior, with particular emphasis on seasonal variability.

3.5.3.1 VFS vs. NV: Wave attenuation by *P. oceanica* over different substrate types and SCIs

Figure 3.5.5 illustrates the cyclic, monthly mean reduction in H_s and U_b throughout the year (Oct'16 - Nov'17), averaged across *P. oceanica* over different substrates and SCIs, attributable to the presence of flexible vegetation canopies with seasonal effect, given by the difference between VFS and NV configurations. During the summer months, the leaves undergo rapid growth due to calm seas, optimal weather and nutrient availability, reaching peak maturity in late summer, followed by the arrival of high waves, which damage the canopies. In winter, wave height attenuation is at its lowest, ranging from 2% - 9% over all SCIs and 1% - 11% across various substrate types, with the strong variation between *P. oceanica* over degraded matte and rocks; similarly for the bottom orbital velocities marking 3% - 8% and 1% - 14% of reduction respectively. From spring through summer, the pattern remains consistent, with average wave reduction around 7% - 9% for both H_s and U_b . This seasonal trend reflects high wave energy and shorter leaf lengths in spring, followed by lower wave energy and developing leaves in summer. When leaf maturity peaks and high waves arrive in September, both factors contribute to maximum wave damping, with reductions of 10% - 18% in H_s over SCIs and 9% - 24% across substrates, and 13% - 20% and 11% - 29% in U_b , respectively. *P. oceanica* growing on sandy and rocky substrates demonstrates a more pronounced impact on wave attenuation compared to degraded matte, which is characterized by lower shoot density and leaf length of *P. oceanica*. Notably, the trends associated with different substrate types do not follow the expected seasonal patterns in Figure 3.4.2, suggesting that *P. oceanica* meadows on rocky substrates exhibit greater wave dissipation capacity than those on sandy substrates during summer, despite the observed variations in leaf length and shoot density. This discrepancy can be attributed to the spatial distribution of the meadows, as illustrated in Figure 3.4.1a, where *P. oceanica* over sand is located farther from the shore compared to those on rocks. Given that wave dissipation (Eq. 3.2.3) is a function of the ratio of leaf length to water depth, this spatial arrangement influ-

ences dissipation efficiency, as also demonstrated in great detail by the laboratory experiments of Anderson and Smith (2014).

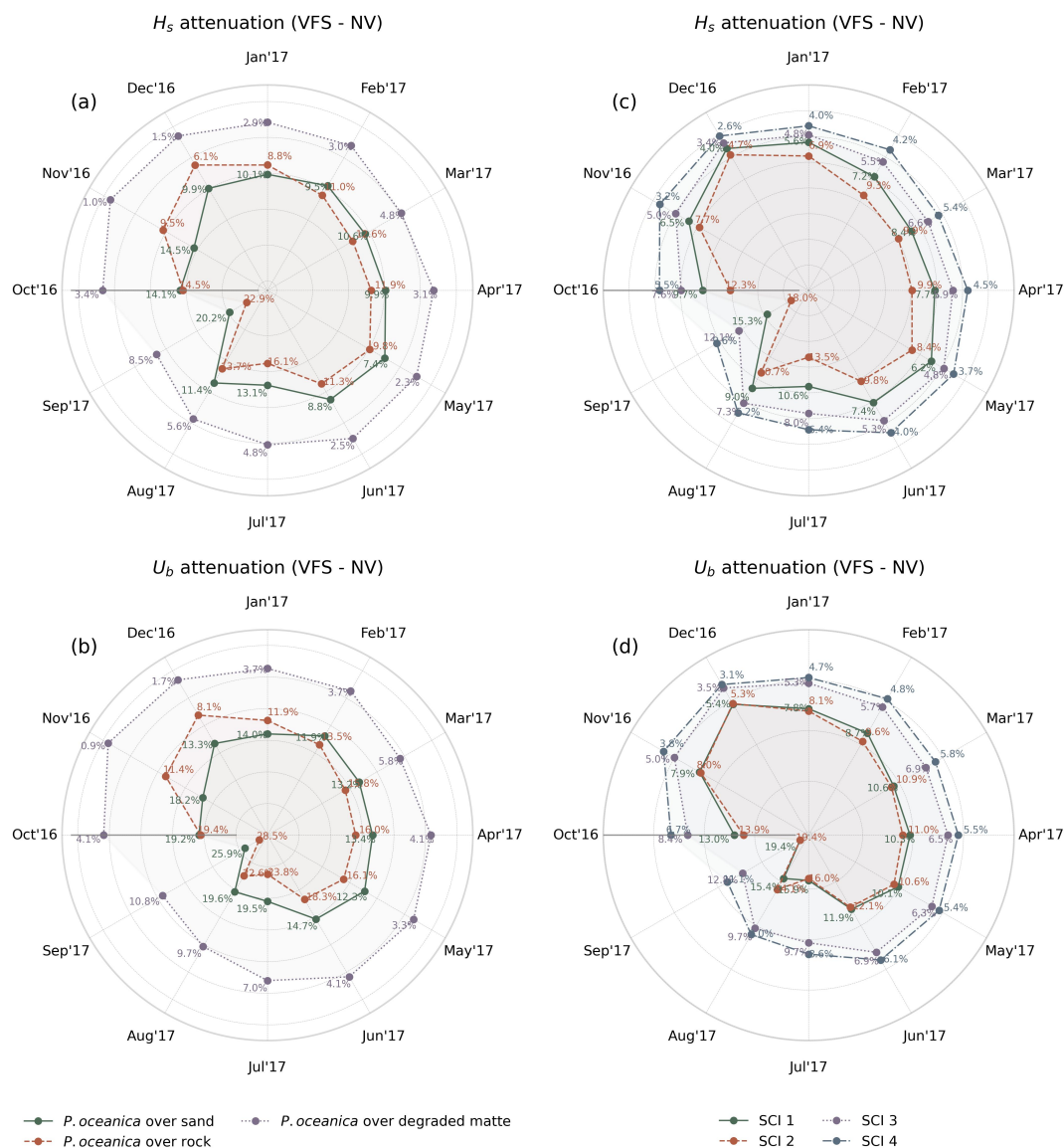


Figure 3.5.5. Mean monthly H_s and U_b percentage reduction (VFS experiment) for *P. oceanica* over different substrates (a,b), and four SCIs (c,d), averaged across vegetated points in the mask.

3.5.3.2 VFS vs. VF: The contribution of seasonal variability of seagrass leaf length

To isolate the seasonal impact of the vegetation model on wave damping, we compare the VFS and VF experiments across different substrates. Figure 3.5.6's bar chart illustrates the percentage differences between the two simulations considering the phenotypic traits of *P. oceanica*. Seasonal variations in seagrass growth lead to a positive difference during late autumn, winter, and spring, reflecting reduced wave attenuation capacity, followed by a shift to a negative difference in summer and early autumn, indicating enhanced wave damping efficiency. The maximum monthly difference is observed over rocks, reaching 10% and 13% for H_s and U_b respectively. The standard deviation across all substrates over seasonal cycle is 5% and 7% (depicted by a solid line), as seen earlier in Section 3.5.3. Overall, the seasonal patterns conform to the growth curves in Figure 3.4.2.

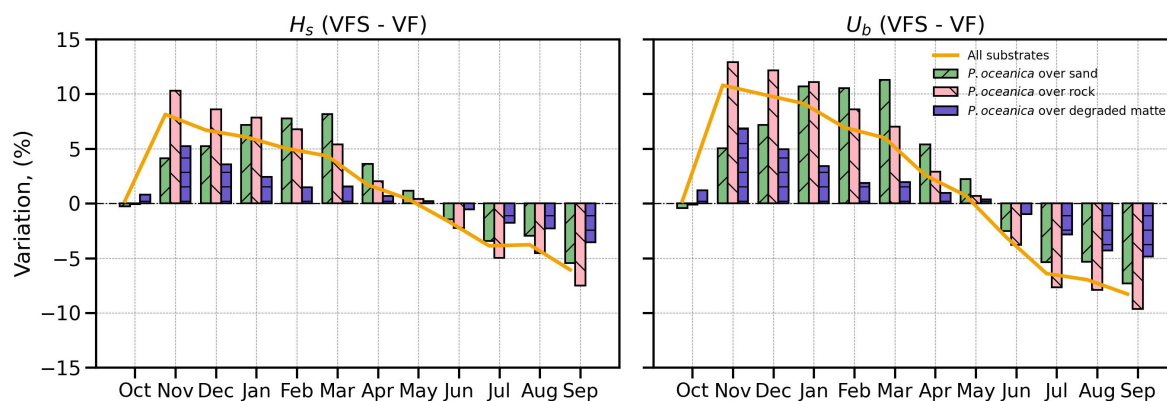


Figure 3.5.6. Timeseries of mean monthly H_s and U_b percentage difference between VFS and VF simulations across substrate types ($(H_{VFS} - H_{VF})/H_{VF} \times 100$). Bars indicate the average differences over vegetated points for each substrate, while the solid orange line represents the weighted average across all vegetated areas in the domain.

3.5.3.3 Seasonal wave attenuation maps

Figure 3.5.7 illustrates the node-wise H_s attenuation capacity of vegetated areas along the Civitavecchia coast by quantifying the wave height reduction attributable to flexible canopies and their seasonal growth patterns. The wave height reduction ranges from 20% to 40% in the SCI 1 and 2 regions (north of Civitavecchia port) and from 10% to 30% in SCI 3 and 4. This discrepancy can be attributed to several factors, such as partial sheltering by S. Marinella headland (Section 3.5.1), seagrass distribution (Figure 3.4.1a), and lower wave damping capacity of *P. oceanica* over degraded matte (Section 3.5.3.1). SCI 2 exhibits the highest wave attenuation capacity, attributed to its predominantly rocky substrate and direct wave exposure. Seasonally, peak wave attenuation occurs during the JAS period (d), driven by intense storm events and the canopy reaching its maximum height. Lower values are observed in winter and spring (a, b, c) due to the presence of predominately juvenile leaves.

3.6 Discussion

Among marine phanerogams, *P. oceanica* has a high capacity for wave attenuation as it forms extensive and dense meadows in coastal areas, with leaves that frequently exceed one meter in length (Koftis et al. (2013)). Due to changing wave energies, *P. oceanica* meadows bend and straighten, causing varying stresses depending on wave orbital velocities, reducing shear and leading to a lower wave damping effect.

As proposed by Luhar and Nepf (2011) and further refined in Luhar and Nepf (2016), the flexibility effect was incorporated into the source term of WW3 by replacing the vegetation leaf length with an effective length as a function of the bottom orbital velocity. Due to the plant's partial passive movement with the wave, this new configuration results in a reduced wave height attenuation compared to that for a fully rigid blade of the same geometry (Lei and

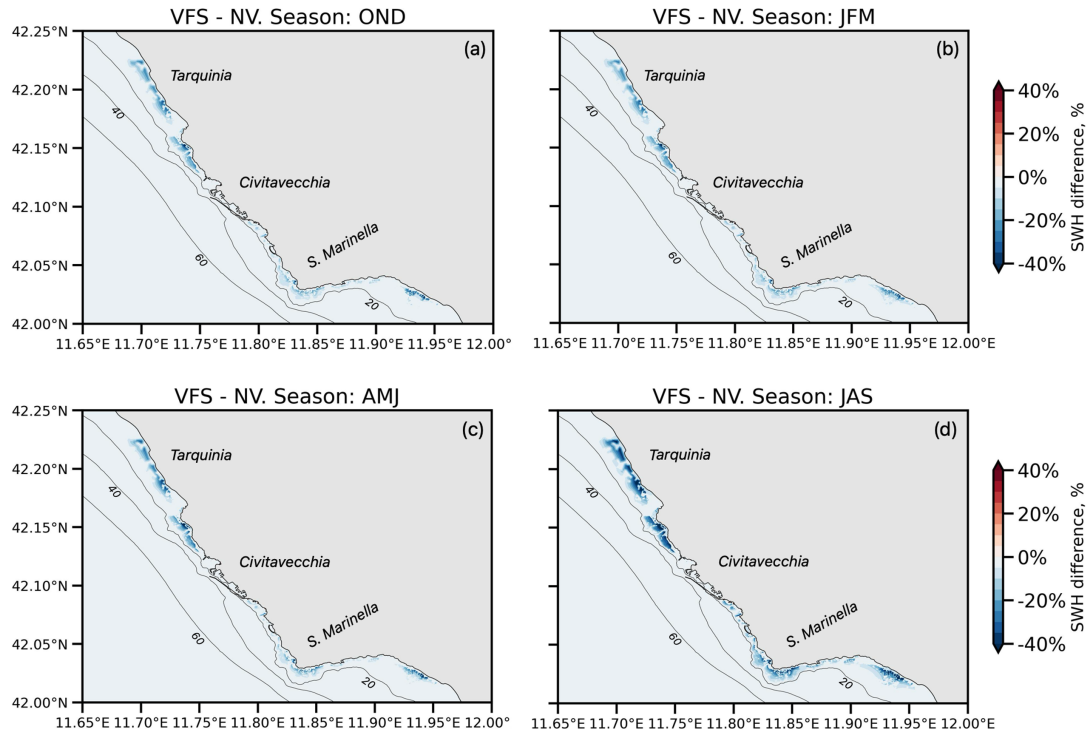


Figure 3.5.7. Maps (zoomed over the coastal area) of seasonal (OND, JFM, AMJ, JAS) mean SWH attenuation (VFS - NV).

Nepf (2019)). Similar to the findings of Beudin et al. (2017), we observed the impact of submerged seagrass on wave characteristics in terms of reduced wave steepness and a localized increase in mean wavelength. Figure 3.6.1 illustrates the impact of vegetation on wave characteristics. As in Beudin et al. (2017), we note the reduction in wave steepness toward the shore as waves interact with seagrass patches. This reduction arises from a combination of wave height damping and a localized increase in the mean wavelength. The latter reflects a spectral shift resulting from seagrass preferentially attenuating shorter, high-frequency waves, rather than an elongation of individual wave components. Such frequency-dependent attenuation has been documented in previous studies, where submerged aquatic vegetation acts as a low-pass filter,

selectively damping higher-frequency wave components and allowing longer-period waves to propagate more effectively (Nowacki et al. (2017); Bradley and Houser (2009)).

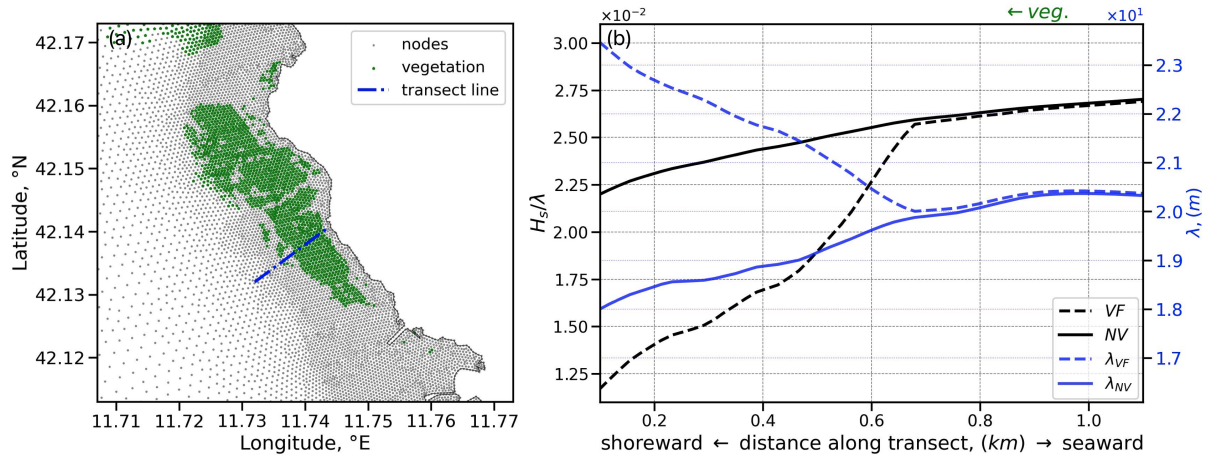


Figure 3.6.1. The impact of vegetation on wave characteristics. (a) Transect line at SCI 2 site, near P05 sampling station; (b) Wave steepness and mean wavelength profiles (annual means) along the transect line, where the shore end is the origin of the x-axis.

To explore how incorporating flexibility can improve model performance and better simulate the effects of seagrass meadows on wave attenuation, a test case was designed to replicate the experiment of Infantes et al. (2012) in the Balearic Islands, where wave parameters were measured for over a month within a *P. oceanica* meadow with known shoot density and leaf length. The model results demonstrated a markedly improved agreement with observed data, achieving wave damping of up to 40-50% for peak energies, compared to the rigid vegetation experiment, which substantially overestimated it at around 80%. Additionally, the model produced a cross-shore variation of wave height that more accurately mimics the nonlinear characteristics inherent in the complex interaction between waves and a flexible canopy.

In application to the Civitavecchia case study, at seasonal scale, we observed an additional monthly wave damping variability of up to 10%, averaged across *P. oceanica* over different substrate types, attributed to the seasonality effect in contrast to the flexible vegetation model

alone. Reduced wave dissipation rates were observed until June, when leaf lengths surpassed the annual averages established for each phenotypic trait in the non-seasonal experiment, VF, after which wave damping increased toward the end of the seasonal cycle in September. Thus, the lack of seasonal variability in the model leads to a misrepresentation of seagrass wave damping efficacy, overestimating its impact in winter and spring, and underestimating it in summer and autumn.

From a spatial point of view, in terms of SCI sites, the model showed a wave damping of approximately 10% during peak waves in March for SCI 2 on average. As both SCI 1 and SCI 2 are predominantly composed of rocky substrates and are exposed to direct waves from the southwest, they experience a greater impact and, consequently, more significant wave reduction compared to SCI 3 and SCI 4. The maximum wave damping reached 16% - 18% on average in September over SCI 1 and SCI 2, and 10% - 12% over SCI 3 and SCI 4. The seasonal effect did not show a linear correlation with the monthly average wave reduction across SCIs when compared to non-vegetated simulation. This aligns with the vegetation model, where wave dissipation is closely related to both wave energy levels and leaf length. Similarly, we observed consistent results in the analysis of wave damping across various substrate types, with peak SWH reductions of 24%, 22%, and 9% for *P. oceanica* traits over rock, sand, and degraded matte, respectively. It's noteworthy that SCI 4, characterized by a higher concentration of degraded matte, exhibited a lower wave attenuation capacity of maximum 10%.

The improved predictive skill demonstrated by the flexible and seasonal vegetation formulations represent a reduction in model overestimation and a more physically realistic representation of wave-canopy interactions under intra-annual wave conditions. The quantified wave attenuation effects are fundamentally limited by the mechanical constraints of the seagrass themselves, and care must therefore be exercised when extrapolating these results to operational contexts, ensuring that the benefits of vegetation are understood within their appropriate physical and ecological bounds.

It is important to note that the seasonality effect is applied to the Civitavecchia site with coefficients empirically derived from site measurements. Consequently, this approach relies on fitted growth curves known for the site of interest, although it can be adapted for use in other areas, provided that the observational data are available. Here, however, the development was specifically tailored to accurately estimate the dynamics of the Civitavecchia coastal region. Seasonal variation was primarily tracked by monitoring the extension of leaf length over time, without considering the decline in size, coverage, and shoot density in recent decades (Marbà et al. (2014); Telesca et al. (2015)) due to a combination of anthropogenic impacts (i.e., boat anchoring, siltation, etc.) and climate change (i.e., introduction of exotic species, the rise of sea surface temperature, and the intensification of wave energy along the coastal zone). The measurements used to reproduce the behavior of *P. oceanica* were obtained through point-based scuba diving observations, which are inherently non-synoptic and spatially heterogeneous. High-resolution spatial and temporal studies typically require extensive in situ data collection, which is both costly and time-consuming. Therefore, the adoption of innovative monitoring techniques, such as autonomous vehicles (e.g., Unmanned Surface Vehicles – USVs) equipped with acoustic sensors, could significantly enhance both data coverage and synopticity. These systems are capable of measuring seagrass height and coverage in shallow coastal areas that are inaccessible to traditional hydrographic platforms, while also detecting canopy variations induced by severe events (Piazzolla et al. (2024)).

Such events can damage vegetation canopies, leading to the temporary absence of seagrass meadows (Oprandi et al. (2020a)), thereby reducing the wave attenuation effect. This feedback loop from the wave model to the vegetation dynamics was not incorporated into our model. Thus, further investigation into seasonal variations of seagrass is necessary, by incorporating abiotic factors that influence plant population dynamics, such as temperature and irradiance (Zupo et al. (1997)), as well as nutrient availability (Elkalay et al. (2003)). Another important consideration is that relying solely on a wave model, without incorporating circulation

dynamics of the region discussed in Section 3.5.2, overlooks the current-induced turbulence that develops above the seagrass canopy, as investigated by Vettori et al. (2025). Beth Schaefer and Nepf (2022) showed that currents can either amplify or diminish vegetation-induced wave damping depending on wave conditions, and the inclusion of this interaction would represent a valuable enhancement to the present study. As demonstrated by Gacia and Duarte (2001), seagrass meadows, by trapping sediments, enhance sediment deposition and reduce resuspension through flow attenuation, stabilizing the seabed and promoting canopy persistence. Integrating sediment transport processes into such coupled frameworks is essential to unravel how sediment-vegetation interactions govern long-term seagrass resilience.

Chapter 4

Wave- and currents-driven sediment transport and morphodynamics

The following chapter presents the development and application of a wave-current-sediment transport and morphodynamics model, addressing seabed response and feedbacks to hydrodynamic forcing, as conceptually illustrated in Figure 4.0.1. This is accomplished by extending the SHYFEM-MPI model with a Sediment Transport and Morphodynamics (STM) module, detailed in the subsequent sections. In this stage, the benthic boundary layer described in Chapter 3 is excluded, to establish the core hydro-morphodynamic coupling and provide the foundation for subsequent model development. The chapter elaborates on the model's theoretical framework, challenges and numerical implementation, demonstrating its applicability across geometries that span from idealized setups to complex coastal domains driven by atmospheric, wave, and circulation forcing.

4.1 Theory and implementation

Nearshore sediment dynamics are markedly nonlinear as tides, winds, surface waves and river plumes interact across multiple spatial and temporal scales. These natural drivers, combined with anthropogenic pressures such as coastal structures, reflective seawalls, and vegetation loss, modulate sediment budgets and shoreline position, often intensifying long-term erosion and flooding risk in densely populated coastal zones (Afentoulis et al., 2022; Divinsky et al., 2021;

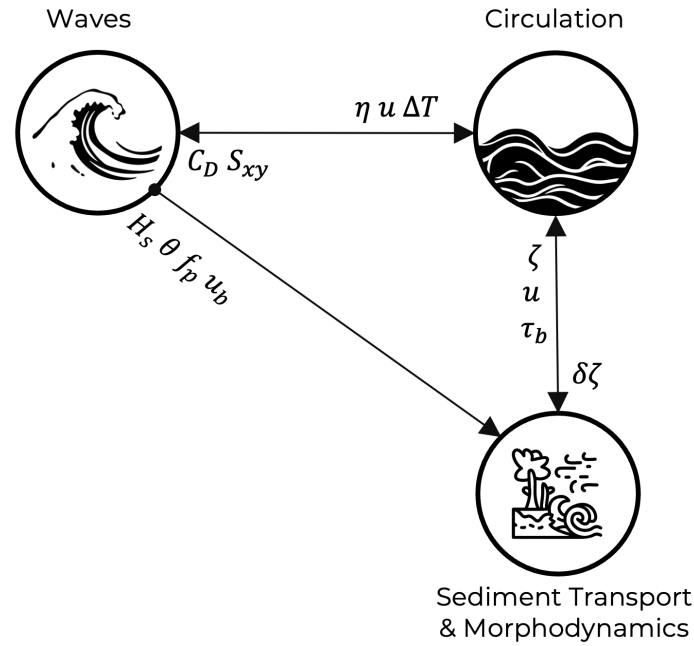


Figure 4.0.1. Schematic representation of the two-way coupling between hydrodynamics (waves and currents) and sediment transport/morphodynamics. The exchange fields and their corresponding symbols are detailed in Figure 1.3.1.

Divinsky and Kosyan, 2020; Roelvink and Costas, 2019; Seabergh and Kraus, 2003). Understanding and predicting sediment transport and morphology feedbacks in such settings is a prerequisite for hazard assessment, infrastructure planning, and ecosystem management.

4.1.1 Dynamics of the bottom boundary layer

At the process level, the Bottom Boundary Layer (BBL) is a central control on morphological adjustment. In shallow and intermediate depths, near-bed flows are typically governed by the combination of oscillatory wave motion and currents, with wave orbital velocities comparable to coastal current magnitudes, while wave-induced bed shear can exceed current-only shear by an order of magnitude during energetic conditions (Grant and Madsen, 1979, 1986). Statistical de-

descriptions of random waves and their induced bottom friction provide a basis for quantifying the distribution and extremes of near-bed shear stress across laminar and turbulent regimes, which in turn regulate the onset of motion, transport mode, and resuspension (Myrhaug, 1995). Classic reviews synthesize the differences between wave- and current-dominated regimes, the formation of bedforms, and the consequences for roughness and transport efficiency in both fluvial and coastal contexts (Graf, 1975; Yalin, 1977; Nielsen, 1992; Fredsoe and Deigaard, 1992; Soulsby, 1997; Van Rijn, 1993, 2007; Julien, 2010). Multiscale two-way wave–current–sediment feedbacks mandate developing coupled/forced models to realistically capture bed and coastal evolution, as well as sediment transport dynamics. This need is amplified by societal exposure, as substantial global populations reside near coastal zones (Clare et al., 2021), and climate-driven changes in sea level and storms will alter coastal morphodynamics in ways that challenge existing defenses (Hinkel et al., 2013). These dynamics are further complicated by benthic layer interactions at seafloor: coastal vegetation, such as saltmarshes, submerged seagrass, and mangroves, significantly alter transport mechanisms by enhancing deposition and trapping suspended particles, thereby influencing local morphology and coastal resilience (Gacia and Duarte, 2001; Chen et al., 2018).

4.1.2 State of the art

A wide spectrum of morphodynamic modelling approaches has emerged over the last four decades (Amoudry et al., 2008; Amoudry and Souza, 2011; Clare et al., 2021). One-dimensional models are computationally efficient but cannot represent cross-stream or vertical structure. Depth-averaged models based on the shallow-water approximation can capture horizontal transport pathways and planform geometry, using finite difference, finite volume, or finite element discretization schemes (e.g., XBeach, MIKE 21, Delft3D) (Warren and Bach, 1992; McCall et al., 2015; Lesser et al., 2004). Three-dimensional models resolve vertical structure and stratification but are more expensive; established frameworks include ROMS, SCHISM, and Delft3D,

which combine free-surface Reynolds-averaged Navier-Stokes equation (RANS) solvers with wave coupling and sediment modules (Warner et al., 2008; Lesser et al., 2004). Finite element and unstructured-mesh systems (e.g., TELEMAC-SISYPHE, Thetis) offer geometric flexibility, local conservation, and scalable parallelism on complex coastlines for advection-dominated transport (Hervouet, 2007; Kärnä et al., 2018). These frameworks increasingly support internal or external coupling to spectral wave models (e.g., SWAN, WW3), enabling consistent exchange of radiation stresses, wave-enhanced roughness and drag, and wave–current interactions on shared or mapped meshes (Wu et al., 2011).

4.1.3 Concept of sediment transport modelling

Across models, sediment transport is commonly decomposed into bedload and suspended load, with bed evolution governed by Exner’s equation and bed feedbacks mediated through roughness and bedforms. Semi-empirical predictors remain the standard approach for estimating transport rates, while unified bedform-roughness formulations connect flow mobility to ripple, megaripple, or dune geometry and the partitioning of skin and form drag (Soulsby, 1997; Van Rijn, 2007; Tassi and Villaret, 2014). Under wave-dominated regimes, boundary-layer structure, sheet flow, and oscillatory stresses demand physics and parameterizations that differ from purely current-driven transport, particularly in the surf zone where depth-limited breaking and strong gradients in radiation stress prevail (Grant and Madsen, 1986). Robust validation and test cases, spanning laboratory flumes to field-scale settings, are essential to constrain model choices and parameter ranges, a need repeatedly emphasized for high-performance morphodynamic models (Syvitski et al., 2010; Villaret et al., 2013a). However, on a large scale domains, the challenges of data availability and resolution persist. The satellite era has expanded observational capabilities, with remote sensing providing synoptic views of shoreline change, turbidity plumes, grain size distribution, and suspended sediment concentrations (Varghese et al., 2024; Benincasa et al., 2019; Pitarch et al., 2019; Volpe et al., 2011; Noori et al., 2023).

4.1.4 Challenges and study outline

Despite substantial progress, the key challenge is to assemble a model to represent complex coastal and estuarine environments, with nonlinear interactions across scales, while managing computational cost and uncertainty due to unresolved physics and the lack of seamless transitional formulations across flow regimes and sediment classes as well as the definitive formulations to the near bed boundary processes under diverse conditions. Bed roughness and bedform formulations are often calibrated for specific settings, and their generalizability is uncertain. Moreover, bedload transport is intrinsically slope-dependent: spatial gradients in bed elevation modify the effective Shields stress and introduce gravity-driven components that reorient and modulate transport rates, evident on riverine systems. Robust assessment therefore demands high-resolution, uncertainty-characterized bathymetric and topographic datasets capable of resolving local bed slopes and their variability. This necessitates the local high-resolution bathymetric data collection efforts.

In this study, we implement and apply a three-dimensional, wave-forced sediment transport and morphodynamics model embedded within a circulation core. The following sections are organized to demonstrate the model's capabilities across different environments. Section 4.2 describes the model's formulation, implementation, and limitations. Section 4.3.1 presents an idealized tidal inlet test case (Warner et al., 2008) to assess performance under wave-dominant conditions and to conduct inter-model comparisons. Section 4.3.2 extends the model to a meandering river (Yen and Lee, 1995) to evaluate current-driven bedload transport under fluvial conditions on a fine domain. Finally, Section 4.3.3 applies the model to the Fiumicino coast at the Tiber river mouth, leveraging an extensive observational dataset of sediment distributions, bathymetric surveys and satellite observations, validating its performance on a complex domain. The key findings and implications of this work are synthesized in Section 4.4.

4.2 Methodology

4.2.1 Model implementation and limitations

Building on the foundational works of Van Rijn (1984), Van Rijn (1993), and Soulsby (1997), this study implements the STM modules within the parallel circulation model SHYFEM-MPI (Micaletto et al., 2022). The parallel architecture, based on the Message Passing Interface (MPI) (The MPI Forum, 1993), is crucial for managing the computational cost, which scales with the number of sediment classes, as each class is handled as an independent tracer field requiring its own advection-diffusion solution. Accordingly, the STM components developed in this study were designed and optimized to operate efficiently within the model's distributed-memory parallel framework. The implementation adapts and advances on the earlier developments of the sediment transport model by Neumeier et al. (2008), Ferrarin et al. (2010), and Li and Amos (2001). The z^* vertical discretization is adopted, a free-surface following scheme described in detail by Verri et al. (2023). Wave forcing fields are supplied by the WW3 spectral wave model (WW3DG), extending on the work discussed in Chapter 2. Wave forcing is provided through an offline (one-way) coupling to manage implementation complexity and focus on the direct impact of waves on sediment transport. Consequently, feedback from morphological changes to the wave field is not included. Nevertheless, the critical feedback to the circulation model is retained, with bathymetry updated at each morphodynamic step, thereby modifying the near-bed velocity and shear profiles. This evolving seabed also adjusts the free-surface elevation through the bathymetry change term, $\partial_t \zeta$, in the continuity equation (Section 4.2.2.3), ensuring the hydrodynamics dynamically adapt to the changing morphology. The circulation and wave models use the same unstructured grid, which ensures one-to-one match and eliminates the necessity of results interpolation, therefore reducing bias. Wave parameters (see Figure 4.0.1) are read within SHYFEM-MPI and partitioned accordingly, with internal linear interpolation for the adaptive time stepping mechanism of the model.

We must note that the use of z^* discretization for sediment transport has inherent limitations, as the bottom layer exhibits a stepwise discontinuity. This characteristic restricts the applicability of morphodynamics due to the additional source of error involving algorithmic trapping mechanism induced by velocity convergence at neighbouring vertex layer boundaries. Consequently, morphodynamic simulations are confined to cases involving small bed-level variations, non-bed-intersecting water column discretizations, or depth-averaged model configurations. However, given the varying sediment classes and depths spanning from the shallow to deep waters, such vertical discretisation reduces computational domain significantly, although traditional models employ terrain-following sigma layers (σ) for sediment transport, which ensure continuity at the bottom boundary layer at the cost of increased computational demand. To address this issue future work will be considered to merge the generalized σ -layers with the geopotential z coordinate system, creating a hybrid solution that ensures continuity at sloping shallow and riverine waters, while maintaining computational efficiency at deeper waters.

4.2.2 Governing equations

The mathematical formulation of the morphodynamic model is rooted in the conservation of sediment mass. Sediment transport is represented through two principal modes: the *suspended load*, advected and diffused throughout the water column, and the *bedload*, moving within a thin layer near the seabed. The governing equations presented below describe the coupled dynamics of these transport modes and their feedbacks with the evolving bed morphology. We first introduce the three-dimensional advection–diffusion equation for suspended sediment concentration, together with the boundary conditions that govern erosion and deposition fluxes at the bed. Next, the temporal evolution of bed elevation is obtained from the Exner equation (Paola and Voller (2005)), which ensures sediment mass conservation by linking the divergence of both suspended and bedload fluxes to changes in seabed elevation. Finally, the morphodynamic feed-

back on hydrodynamics is closed through the continuity equation for the free surface, thereby maintaining two-way coupling between sediment transport, bed evolution, and the flow field.

4.2.2.1 Advection-diffusion of suspended sediments

Suspended sediment transport is typically described by an advection-diffusion equation (Galappatti and Vreugdenhil (1985)), similar to other tracers as detailed in Micaletto et al. (2022), and in general form it reads:

$$\frac{\partial C}{\partial t} + \nabla_h \cdot (\mathbf{u}_h C) + \frac{\partial[(w - w_s)C]}{\partial z} = \nu_h \nabla_h^2 C + \nu_v \frac{\partial^2 C}{\partial z^2} + F \quad (4.2.1)$$

where C is the sediment concentration (kg/m^3), $\mathbf{u}_h = (u, v)$ is the horizontal velocity vector (m/s), w is the vertical velocity (m/s), and w_s is the settling velocity (m/s), ν_h and ν_v are the horizontal and vertical eddy diffusivities (m^2/s), computed through Smagorinsky (1963) and Burchard and Petersen (1999b) turbulence closure schemes, respectively, and F represents additional sources or sinks. Integrating 4.2.1 over the layers h_l , as described in Verri et al. (2023) for z^* discretisation, it takes the following form:

$$\begin{aligned} \frac{\partial(h_l C_{l(i)})}{\partial t} + \nabla_h \cdot (\mathbf{U}_h C_{l(i)}) + \int_{z_l^*}^{z_{l-1}^*} \frac{\partial[(w_l - w_{s(i)}) C_{l(i)}]}{\partial z^*} dz^* = h_l \nu_{h,l} \nabla_h^2 C_{l(i)} + \\ \int_{z_l^*}^{z_{l-1}^*} \nu_{v,l} \frac{\partial^2 C_{l(i)}}{\partial z^{*2}} dz^* + F \end{aligned} \quad (4.2.2)$$

where the indices i and l indicate the sediment class and vertical layer respectively, with h being the layer thickness (m), and $\mathbf{U}_h$ the layer-integrated horizontal transport vector. The vertical

boundary condition for 4.2.2 is given by (Ferrarin et al. (2008)):

$$-\nu_{v,\eta} \left. \frac{\partial C_{(i)}}{\partial z^*} \right|_{z^*=\eta} + w_{s(i)} C_{\eta(i)} = 0, \quad (4.2.3)$$

$$+\nu_{v,\zeta} \left. \frac{\partial C_{(i)}}{\partial z^*} \right|_{z^*=\zeta} + w_{s(i)} C_{\zeta(i)} = \Gamma_{(i)} \quad (4.2.4)$$

where Γ ($kg/(m^2s)$) represents a flux of matter between the water column and the seafloor, represented as the difference of eroded (E) and deposited (D) sediments. The components for these fluxes are defined at the bed interface ($\Delta z = \lim_{\delta \rightarrow 0^+} (\zeta + \delta)$) based on a near-bed C_ζ and an equilibrium C_{eq} concentrations:

$$D = C_{\zeta(i)} \left(\frac{\nu}{\Delta z} + w_{s(i)} \right) \quad (4.2.5)$$

$$E = C_{eq(i)} \left(\frac{\nu}{\Delta z} \right) \quad (4.2.6)$$

where ν is the kinematic viscosity of the fluid; C_{eq} is the equilibrium concentration that the flow can support. The sediment profile reconstruction follows Rouse distribution and is detailed in Section 4.2.2.11.

4.2.2.2 Seafloor evolution

The temporal evolution of the seabed elevation, $\partial \zeta / \partial t$, is governd by the Exner equation (Paola and Voller, 2005; Villaret et al., 2013b), with the contributions from the suspended sediment flux Γ and the bedload transport vector $\mathbf{Q}_b = (q_{b,x}, q_{b,y})$ ($kg/(ms)$). In its differential form, the Exner equation thus reads:

$$\frac{\partial \zeta}{\partial t} = \frac{m}{\rho_s(1-p')} (\nabla_h \cdot \mathbf{Q}_b - \Gamma) \quad (4.2.7)$$

where p' is the bed surface porosity set to 0.5, m is a morphological factor (Gerritsen et al. (2007)), ∇_h is the horizontal divergence operator (m^{-1}), and $\mathbf{Q}_b$ components are detailed in Section 4.2.2.10.

4.2.2.3 Free surface

Morphological adjustments of the seabed induce perturbations in the overlying water column, which, through mass-continuity, manifest as changes in the free surface elevation, η (m). Deriving the sea surface elevation from the mass continuity equation with a component of time rate of change of seabed elevation $\zeta(x, y, t)$ (positive downwards), we obtain:

$$\frac{\partial \eta}{\partial t} = \frac{\partial \zeta}{\partial t} - \nabla_h \mathbf{U}_h - q_w - \frac{1}{\rho_0} \int_{\zeta}^{\eta} \frac{D\rho'}{D\rho} dz^* \quad (4.2.8)$$

where q_w is a normalized fresh water flux as in Pinardi et al. (2014), $\mathbf{U}_h$ is the depth-integrated horizontal transport vector (m^2/s). This formulation is complacent with the definitions of Vallis (2017) for shallow water system and Roos and Hulscher (2003).

The definition of the normalized coordinate z^* (Verri et al. (2023)) here is extended to account for the time-dependent bed elevation $\zeta(x, y, t)$, replacing the static bathymetry by the evolving bed due to sedimentation and erosion processes as follows:

$$z^*(x, y, z, t) = \frac{z - \eta(x, y, t)}{\zeta(x, y, t) + \eta(x, y, t)} \zeta(x, y, t) \quad (4.2.9)$$

where z represents the fixed vertical coordinate in the underlying geopotential (z -level) discretization.

4.2.2.4 Radiation stresses

Surface gravity waves exchange momentum with currents through the radiation-stress or vortex-force (Longuet-Higgins and Stewart, 1961; Mellor, 2003; Ardhuin et al., 2008; McWilliams et al., 2004). The radiation-stress tensor components S_{xx} , S_{xy} , and S_{yy} describe nearshore wave transformations and the associated excess momentum flux. Following Longuet-Higgins and Stewart (1961), wave setup/setdown arises from a balance between horizontal gradients of radiation stress and the sea-surface pressure gradient. The corresponding depth-integrated

wave-induced momentum flux F is included in the momentum equations and is given by the horizontal divergence of the radiation-stress tensor as in Eq. 2.2.1

4.2.2.5 Sediment motion initiation criteria

The critical shear stress is defined as the bed shear stress at which sediment particles begin to move, representing the threshold of motion. With increasing stress, sediment particles are initially entrained from rest and subsequently undergo three distinct modes of transport: bedload, suspended load, and sheet-flow (Li and Amos (2001)), only first two of which are considered here. Bedload transport is initiated based on the following criteria in a form obtained by fitting the Shields curve proposed in Soulsby and Whitehouse (1997):

$$\theta_{cr,b} = \frac{0.30}{1 + 1.2 \cdot d_*} + 0.055[1 - \exp(-0.020 \cdot d_*)] \quad (4.2.10)$$

$$u_{cr,b}^* = \sqrt{\theta_{cr,b} \cdot (s - 1) g d_{50}} \quad (4.2.11)$$

$$d_* = d_{50} \left[\frac{g(s - 1)}{\nu^2} \right]^{1/3} \quad (4.2.12)$$

where $\theta_{cr,b}$ is the critical Shields parameter for bedload transport initiation, $u_{cr,b}^*$ is the corresponding critical shear velocity, $s = \frac{\rho_s}{\rho_w}$ is the relative density of sediments (ρ_s) to the fluid (ρ_w), and d_* is a dimensionless grain size parameter. The relationship between shear stresses and shear velocities is expressed as $\tau = \rho_w u^*$, therefore, the corresponding critical stress for the bedload transport initiation for Eq. 4.2.11 is $\tau_{cr,b}$. This threshold is then calibrated using the slope effect at inclined beds, which induces or restricts the movement computed as per Soulsby (1997):

$$\alpha = \frac{\cos(\phi) \sin(\theta) + \sqrt{\cos^2(\theta) \tan^2(\beta) - \sin^2(\phi) \sin^2(\theta)}}{\tan(\beta)} \quad (4.2.13)$$

where θ is bed slope angle, ϕ is an angle between slope aspect and transport direction, and β is the angle of repose. The settling velocity for non-cohesive sediment particles is computed based

on average sediment grain sizes (d_{50}) and kinematic viscosity of the fluid (ν), as formulated below (Tassi et al., 2023; Clare et al., 2021; Soulsby, 1997):

$$w_s = \begin{cases} \frac{g \cdot d_{50}^2}{18 \cdot \nu} \cdot (s - 1) & \text{if } d_{50} < 0.0001 \text{ m} \\ 10 \cdot \left(\frac{\nu}{d_{50}} \right) \cdot \left(\sqrt{1 + 0.01 \cdot \frac{(s - 1) \cdot g \cdot d_{50}^3}{\nu^2}} - 1 \right) & \text{if } 0.0001 \leq d_{50} < 0.001 \text{ m} \\ 1.1 \cdot \sqrt{(s - 1) \cdot g \cdot d_{50}} & \text{otherwise} \end{cases} \quad (4.2.14)$$

However, such formulation is piecewise and discontinuous. Another, universal settling velocity proposed by Ferguson and Church (2004) is adopted, which estimates the fall velocity of sediment particles across a wide range of sizes and flow regimes, transitioning between the laminar and turbulent settling regimes:

$$w_s = \frac{(s - 1)gd_{50}^2}{C_1\nu + \sqrt{0.75C_2(s - 1)gd_{50}^3}} \quad (4.2.15)$$

For smooth, spherical particles, Ferguson and Church (2004) recommend $C1 = 18$ and $C2 = 0.4$ coefficients, for natural, irregularly shaped grains, values of $C1$ between 20 – 24 and $C2$ between 1.0 – 1.2 are suggested to account for increased drag due to shape irregularities.

The following criteria represents the threshold for resuspension of the sediments off the bed. Sediments are resuspended according to Van Rijn (1993) Sields criteria with the dependency on settling velocity (Eqs. 4.2.14, 4.2.15):

$$\theta_{cr,s} = \begin{cases} \frac{16}{d_*^2} \frac{w_s^2}{(s - 1)gd_{50}}, & 1 < d_* \leq 10, \\ 0.16 \frac{w_s^2}{(s - 1)gd_{50}}, & d_* > 10, \end{cases} \quad (4.2.16)$$

$$u_{cr,s}^* = 5.75 \log \frac{12h}{k_s} \sqrt{\theta_{cr,s}(s - 1)gd_{50}} \quad (4.2.17)$$

where $u_{cr,s}^*$ is the critical shear velocity for initiation of resuspension. This concludes the computation of thresholds for distinguishing between the sediment motion regimes.

4.2.2.6 Bed roughness

The total roughness of the seabed is induced by sediment grains, small-scale bedform or ripples, and dunes (Julien (2010)). Bedform represent roughness elements for wave- and current-driven flows, controlling to a large degree the structure of the boundary layer (Grant and Madsen (1986)). There are different bedform parameterizations depending on main flow characteristics, which are summarised by Julien (2010). Here we adopt the formulations of Van Rijn (2007), where the combined wave-current flow regime is accounted for and the bedform is parameterized as a function of the dimensionless mobility parameter, Ψ :

$$\Psi = \frac{u_{wc}^2}{(s-1)g d_{50}}, \quad (4.2.18)$$

where $u_{wc}^2 = u_c^2 + u_{w,rms}^2 + 2u_c u_{w,rms} \cos \phi$ with $u_{w,rms} = u_b/\sqrt{2}$, and ϕ is the phase angle, or an angle between wave and current vectors, $|\theta_w - \theta_c|$ *rad*. The skin roughness and short-wave ripple roughness heights are expressed as:

$$k_s = 2.5 d_{50} \quad (4.2.19)$$

$$k_{s,r} = f_{cs} d_{50} [85 - 65 \tanh(0.015(\Psi - 150))] \quad (4.2.20)$$

where $f_{cs} = \min(1, (0.25 d_{\text{gravel}}/d_{50})^{1.5})$ is a correction factor which accounts for the reduction of ripple roughness on coarser sediment beds. The megaripples and dunes are modulated by the fine-sand factor $f_{fs} = \min(1, d_{50}/(1.5 d_{\text{sand}}))$, with $d_{\text{sand}} = 0.062\text{mm}$, and predicted as follows:

$$k_{s,mr} = 2 \times 10^{-5} f_{fs} h (1 - e^{-0.05\Psi}) (550 - \Psi) \quad (4.2.21)$$

$$k_{s,d} = 8 \times 10^{-5} f_{fs} h (1 - e^{-0.02\Psi}) (600 - \Psi) \quad (4.2.22)$$

All components combine by quadratic summation (Tassi and Villaret, 2014; Soulsby, 1997; Julien, 2010) to yield the effective total roughness height:

$$k_{s,\text{tot}} = k_s + \sqrt{k_{s,r}^2 + k_{s,mr}^2 + k_{s,d}^2} \quad (4.2.23)$$

Finally, the apparent roughness height is a function of the total bedform roughness and increases exponentially with the product of the amplification factor, γ , that depends on the angle between currents and waves (Van Rijn (1984)), $\gamma = 0.8 + \phi - 0.3\phi^2$, and the ratio of wave orbital velocity u_b to an ambient velocity u_a :

$$k_a = k_{s,tot} \cdot e^{\gamma u_b/u_a} \quad (4.2.24)$$

The Nikuradse roughness length is then defined as

$$z_0 = \frac{k_a}{30} \quad (4.2.25)$$

4.2.2.7 Bottom friction

The sediment motion is initialised when the critical thresholds described in Section 4.2.2.5 are surpassed. The wave action and the bottom flow velocity induce stresses at the seafloor that may exceed these thresholds and instigate the morphological changes. The maximum stress due to isolated wave action, τ_w , can be expressed as:

$$\tau_w = 0.5\rho_w f_w u_b^2 \quad (4.2.26)$$

where f_w is the wave friction factor that can be computed for all flow regimes (A_w/k_a) as suggested by Soulsby (1997):

$$f_w = 0.237(A_w/k_s)^{-0.52} \quad (4.2.27)$$

where T is wave period, $A_w = u_b/\omega$ - wave excursion, $\omega = 2\pi/T$ - wave angular frequency. Nielsen (1992) proposed universal formulation for fully developed turbulent flow regime for known Nikuradse roughness as:

$$f_w = e^{[5.5(A_w/k_s)^{-0.2} - 6.3]} \quad (4.2.28)$$

This formulation is shown to be more stable throughout different experimental domains of this work, and thus is adopted here. The currents induced friction factor, f_c , is given by Van Rijn

(1984) and reads:

$$f_c = 0.24 [\log_{10}(12h/k_s)]^{-2} \quad (4.2.29)$$

The combined friction factor is typically solved numerically following Grant and Madsen (1979), however, it can also be approximated as suggested in Van Rijn (2007):

$$f_{wc} = \sqrt{\alpha_f f_c^2 + (1 - \alpha_f) f_w^2} \quad (4.2.30)$$

where $\alpha_f = u_c/(u_c + u_b)$ is relative strength of wave versus current forcing. The Grant and Madsen (1979) formulation is computationally more expensive, but it is expected to be more accurate, and is used for the idealized test cases in this work, whereas the latter one is more robust and is used for the complex coastal domain.

4.2.2.8 Shear velocity computation

Under the assumption of a fully developed turbulent boundary layer, the friction (shear) velocity due to a steady current is obtained directly from the logarithmic 'law of the wall'. Thus, the velocity field at elevation z above the seabed reads:

$$u_c^* = \kappa \frac{u(z)}{\ln(z/z_0)} \quad (4.2.31)$$

where κ is the von Kármán constant, and z_0 is the roughness length. For purely oscillatory wave-induced motion of amplitude u_b , the shear velocity can be expressed using the computed wave friction factor f_w as:

$$u_w^* = \sqrt{0.5 f_w u_b^2} \quad (4.2.32)$$

Under combined wave-current forcing, the total shear velocity is given by the vector-sum of current-only and wave-only stresses, with ϕ the phase angle between them (Grant and Madsen, 1979):

$$u_{cw}^* = \sqrt{(u_c^*)^2 + (u_w^*)^2 + 2u_c^* u_w^* \cos \phi} \quad (4.2.33)$$

Finally, adapting the same logarithmic form over the wave–current boundary-layer thickness, δ_{cw} , the ambient near-bed velocity u_a is obtained as follows:

$$u_a = \frac{u_{cw}^*}{\kappa} \ln \left(\frac{\delta_{cw}}{k_a} \right) \quad (4.2.34)$$

$$\delta_{cw} = \frac{2\kappa u_{cw}^*}{\omega} \quad (4.2.35)$$

4.2.2.9 Vertical sediment-mixing coefficient

Under the GOTM-based (Burchard and Petersen, 1999a) turbulence closure ($k - \epsilon$ model), the eddy diffusivity for suspended sediment at each vertical level is obtained by scaling the eddy viscosity $\nu(z)$ with a settling-velocity-dependent dimensionless mixing ratio β (Van Rijn, 1993):

$$\beta = 1 + 2 \left(\frac{w_s}{u_{cw}^*} \right)^2 \quad (4.2.36)$$

where the term $(w_s/u_{cw}^*)^2$ represents the relevant strength between downward settling and upward turbulent diffusion, with larger w_s relative to near-bed shear, resulting in stronger deviation from passive mixing. The resulting sediment diffusivity profile, $\varepsilon_s(z)$, then follows directly:

$$\varepsilon_s(z) = \beta \nu(z) \quad (4.2.37)$$

4.2.2.10 Bedload transport

The interaction at the wave-current boundary layer enhances turbulence and bed shear stress compared to currents or waves acting alone. The following intra-wave quasi-steady model (Van Rijn, 1993; Neumeier et al., 2008) computes the sediment transport rate at discrete time steps within a single wave cycle, driven by the instantaneous combined wave-current effective shear stress. The net transport over the wave period is then obtained by time-averaging these instantaneous rates. This method captures the potential effects of wave asymmetry and phase lags between velocity, shear stress, and sediment response. The instantaneous bedload transport

rate, $q_{b,t}$, used in this work (Van Rijn (2007)), reads:

$$q_{b,t} = \gamma \rho_s f_{silt} d_{50} d_*^{-0.3} \sqrt{\frac{\tau_{b,cw}(t)}{\rho_w}} \left[\frac{\tau_{b,cw}(t) - \tau_{b,cr}}{\tau_{b,cr}} \right]^\eta \quad (4.2.38)$$

where the instantaneous combined shear stress magnitude is obtained as:

$$\tau_{b,cw}(t) = \sqrt{\tau_c^2 + \tau_w^2 \sin^2(\omega t) + 2\tau_c \tau_w \sin(\omega t) \cos \phi} \quad (4.2.39)$$

Then $q_{b,t}$ is integrated over the subintervals (crest and trough phases) of the wave period (Neumeier et al. (2008)) to yield the mean bedload transport rate, $\bar{q}_b$, or continuously over the whole period (Van Rijn (2007)) whenever the induced shear stresses exceed the thresholds, with latter one being adopted in the present study. In river channels due to meandering nature and an evolving bed slope, the bedload transport needs to be corrected for the transport magnitude depending on the positive or negative gradients. The formulation in Eq. 4.2.13 is based on Shields criteria and is valid only for the threshold bedload initiation as detailed in Tassi et al. (2023). To adjust the bedload transport rate, the formulation of Koch and Flokstra (1980) is used, which is based on a factor that acts as a diffusion term (Clare et al., 2021; Tassi et al., 2023):

$$\bar{q}_b^* = \bar{q}_b \left(1 - Y \frac{\partial \zeta}{\partial s} \right) \quad (4.2.40)$$

where Y is an empirical coefficient similar to Sisyphe model in Tassi and Villaret (2014), and s being the direction tangential to the flow:

$$s = \left(\frac{\partial \zeta}{\partial x} \cos \alpha + \frac{\partial \zeta}{\partial y} \sin \alpha \right) \quad (4.2.41)$$

The angle α will deviate from that of the shear stress due to the bed slope and helical flow effects necessitating further corrections (Struiksma et al., 1985; Talmon et al., 1995):

$$\tan \alpha = \frac{\sin \xi - \frac{1}{\beta_2 \sqrt{\theta}} \frac{\partial \zeta}{\partial y}}{\cos \xi - \frac{1}{\beta_2 \sqrt{\theta}} \frac{\partial \zeta}{\partial x}} \quad (4.2.42)$$

with δ representing the original angle between sediment transport and flow direction, and θ - the Shields parameter. To account for the secondary currents in two-dimensional models, due to missalined bed shear stress and sediment slope directions, the δ angle is further adjusted following Engelund (1974):

$$\tan \tilde{\delta} = \frac{A}{r_s} h \quad (4.2.43)$$

With the depth-averaged velocity components (u , v) and a spiral flow coefficient $A = 7$, the local radius of curvature, r_s , is defined as (Clare et al., 2021):

$$r_s = \frac{\alpha' (u^2 + v^2)}{g \frac{\partial \eta}{\partial n}} \quad (4.2.44)$$

where n - the direction normal to the current, and $\alpha' \in [0.75, 1.0]$ - a coefficient that depends on bed roughness.

4.2.2.11 Rouse concentration profile

Suspended sediment transport is computed by first determining the hydrodynamic forcing (bed and near-bed stresses, velocity profiles), then estimating the bed-available reference concentration (C_0), deriving the vertical concentration distribution ($C(z)$), and finally integrating the advective flux ($u(z) \cdot C(z)$) over the water column. To resolve strong near-bed gradients we discretize the vertical domain with a power-law stretched grid that concentrates levels close to the bed:

$$z_i = h \left(\frac{i}{N} \right)^p \quad (4.2.45)$$

$$p = \frac{\ln(z_{\min}/h)}{\ln(1/N)} \quad (4.2.46)$$

so that $z(1) \approx z_{\min} = 0.01m$, h - water depth, and the grid spacing increases with height. Using the logarithmic law-of-the-wall for the outer (current-dominated) layer and a two-layer adjustment to represent the wave-currents boundary layer (δ_{cw}), the mean velocity profile is taken

piecewise as

$$u(z) = \begin{cases} \frac{u_{cw}^*}{\kappa} \ln\left(\frac{z}{z_0}\right) & \text{if } z \leq \delta_{cw}, \\ \frac{u_c^*}{\kappa} \ln\left(\frac{z}{z_{0c}}\right) & \text{if } z > \delta_{cw} \end{cases} \quad (4.2.47)$$

where u_{cw}^* is the combined wave–current shear velocity in the inner layer, u_c^* is the current-only shear velocity in the outer layer, z_0 is the bed roughness, and z_{0c} is the apparent roughness length computed using Eq. 4.2.24. The near-bed reference concentration (C_0) is computed using the empirical relation of Zyserman and Fredsøe (1994) with the critical Shields parameter θ_{cr} for incipient motion on dimensionless grain size (d_*) (Soulsby (1997)). Near-bed reference concentration (C_0) is then:

$$C_0 = \frac{0.331(\theta' - \theta_{cr})^{1.75}}{1 + 0.720(\theta' - \theta_{cr})^{1.75}} \quad \text{for } \theta' > \theta_{cr} \quad (4.2.48)$$

and $C_0 = 0$ if $\theta' \leq \theta_{cr}$, where θ' denotes the Shields parameter based on the relevant skin (near-bed) shear stress τ' and (Zyserman and Fredsøe, 1994; Soulsby, 1997). The suspended sediment concentration profile is assumed to follow a Rouse-type distribution in the near-bed region (Rouse, 1937), where for the combined wave–current profile we adopt:

$$C(z) = \begin{cases} C_0 \left(\frac{z}{s_{tot}}\right)^{-\beta_f w_s / (\kappa u_{cw}^*)} & \text{if } z \leq \delta_{cw} \\ C(\delta_{cw}) \left(\frac{z}{\delta_{cw}}\right)^{-\beta_f w_s / (\kappa u_c^*)} & \text{if } z > \delta_{cw} \end{cases} \quad (4.2.49)$$

$$\beta_f = 1 + 2(w_s / u_{cw/c}^*)^2 \quad (4.2.50)$$

where β_f is a correction factor described in Van Rijn (1984), similar to Eq. 4.2.50, depending on the flow conditions (combined / c-only / w-only). The depth-integrated suspended sediment transport within the near-bed layer is then computed as:

$$Q_s = \int_{k_{s,tot}}^{h_{bed}} u(z) C(z) dz \quad (4.2.51)$$

where h_{bed} denotes the thickness of the bottom computational layer in the discretized domain, within which the Rouse profile is assumed to be valid. To improve accuracy in highly stratified velocity and concentration profiles, the Simpson's rule is used with a trapezoidal fallback for the odd number of intervals.

$$Q_s = \sum_{\substack{i=1 \\ i \bmod 2=1}}^{N-3} \frac{h_i}{6} (u_{i-1}c_{i-1} + 4u_i c_i + u_{i+1}c_{i+1}) \frac{h_{N-1}}{2} (u_{N-1}C_{N-1} + u_N C_N) \quad (4.2.52)$$

$$C_s = \sum_{\substack{i=1 \\ i \bmod 2=1}}^{N-3} \frac{h_i}{6} (c_{i-1} + 4c_i + c_{i+1}) \frac{h_{N-1}}{2} (C_{N-1} + C_N), \quad (4.2.53)$$

where $h_i = z_{i+1} - z_{i-1}$, $h_{N-1} = z_N - z_{N-1}$ with the second component under summation as a trapezoid on last layer for odd number of intervals. Finally, the near-bed depth-averaged suspended sediment concentration ($\bar{C}$) is computed by dividing the total suspended amount at last layer (C_s) by the integration depth (bottom layer thickness) (D) as $\bar{C} = C_s/D$.

4.3 Experiments

The following sections apply the developed STM model to a set of idealized test cases designed to validate its formulation and evaluate its performance under varying conditions. The model is then extended to a realistic coastal setting to illustrate its effectiveness in simulating sediment dynamics in natural environments.

4.3.1 Tidal inlet

We set up the idealized tidal inlet test case following the work of Warner et al. (2008), who conducted one- and two-way coupled wave-current experiments (ROMS-SWAN) including sediment transport. ROMS (Shchepetkin and McWilliams, 2005) and SWAN (Booij et al., 1996)

are widely used, community-developed, state-of-the-art circulation and wave models, respectively. The same test case was later adapted by Wu et al. (2011) for the unstructured-grid FVCOM finite volume coastal model (Chen et al., 2012). The latter study demonstrated the value of unstructured grids for resolving inlet dynamics, similar to the domain discretization applied in the SHYFEM-MPI model. In particular, velocity fields from such experiments are essential for assessing flow diffusivity.

4.3.1.1 Inlet domain and model set-up

The computational domain consists of a rectangular basin, 15 km wide and 14 km long, with an initial uniform depth of 4 m inside the lagoon and a sloping bed up to 15 m at the northern half (Figure 4.3.1). The northern side serves as the open boundary (OB), corresponding to the deepest section of the sloping bed. A no-slip condition is imposed on the remaining boundaries. Along the center of the domain is a wall with a centered 2km wide inlet. The model is forced by the semi-diurnal tidal signal at the open boundary with the amplitude of 1m. Waves are imposed on the OB with a wave height of 1m, directed to the south with a period of 10s. The model is run for 48 hours as in the original experiments. Table 4.3.1 summarizes the main parameters used in the tidal inlet test case.

The numerical model was set-up with the TVD limiting vertical advection scheme, the GOTM turbulence closure, and the quadratic bottom friction formulation. The bottom roughness was set to a fixed 0.015 m height, as in the original experiment, similarly with the wave porosity and settling velocity constants. To reconstruct the 3D model, in order to capture the suspended sediment profiles, we used 2 vertical layers, with the first layer at 1.3 m depth and the second spanning through the rest of the water column. Validating sediment transport models is challenging due to the complexity and numerous parameterizations involved in approximating underlying physical processes in a highly dynamic environment. Thus, we focus on comparing the results with the original works of Warner et al. (2008) and Wu et al. (2011), with a qualita-

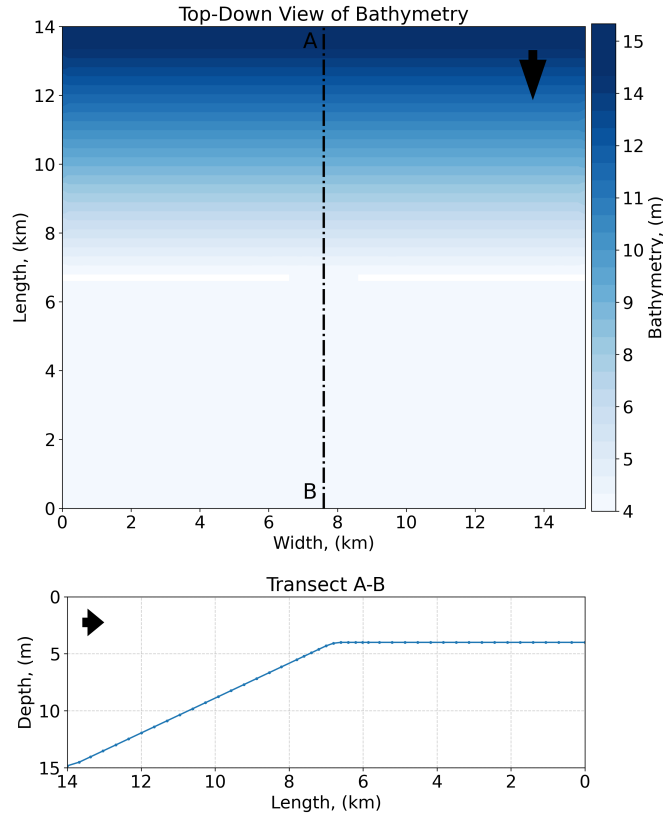


Figure 4.3.1. Tidal inlet domain with top-down look at the bathymetry map (a), and a profile along A-B transect (b). Arrows indicate the flow forcing direction, characterised by the tidal and wave forcing at the open boundary.

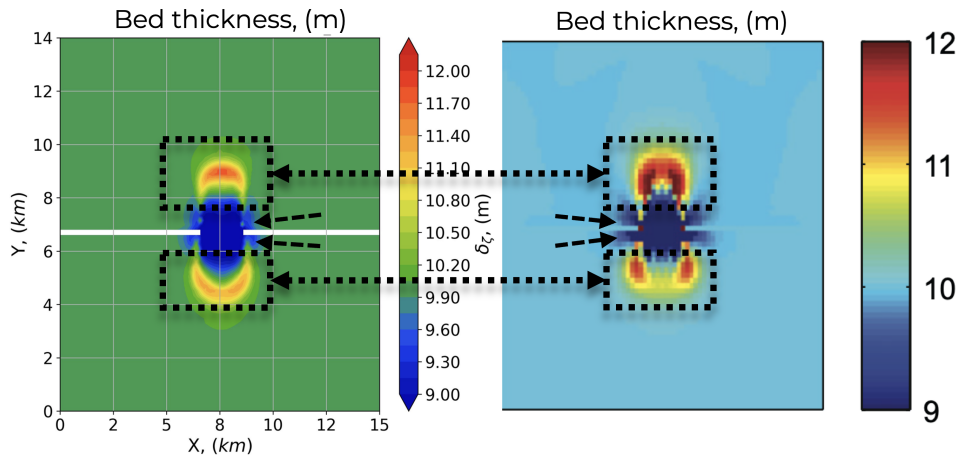
tive assessment of the morphological changes at the inlet, the velocity and sea surface elevation fields.

4.3.1.2 Inlet test results and inter-model comparison

The results of the simulation are shown in Figure 4.3.2, corresponding to 48 hours of simulation. The model captures the shear stresses imposed by the hydrodynamic forcing, driving the bedload and suspended load transport, effectively resulting in the morphological changes at the inlet. The comparison with the Warner et al. (2008) results illustrate similar patterns of bed

Table 4.3.1. Model parameters for tidal inlet test case.

Model parameter	Variable	Value
Bottom roughness	z_b	0.015 m
Time step	dt	Adaptive
Simulation time	t_s	48h (2 days)
Morphology factor	m	10
Settling velocity	w_s	11.0 mm s ⁻¹
Porosity	ρ'	0.50
Semi-diurnal tides amplitude	A	1.0 m
Wave height	H_s	1.0 m
Wave period	T	10 s
Wave direction	θ	From 0 °N

**Figure 4.3.2.** Bed evolution (ζ) comparison between SHYFEM-MPI (left) and ROMS (right) adapted from Warner et al. (2008). The dashed frames indicate similar erosion and deposition patterns corresponding between the two models.

evolution (depicted by arrows) with pronounced erosion along the central channel and deposition on either flank of the inlet. Radial erosion at the inlet mouth and semi-circular deposition within the inner basin are also evident, indicating lateral sediment redistribution. Comparable bed evolution patterns were also reported by Wu et al. (2011) for similarly forced inlet systems.

A qualitative comparison with the results from Wu et al. (2011), who applied the unstructured-grid FVCOM model to the same test case, is illustrated in Figure 4.3.3 for the currents and sea surface elevation to depict the impact on hydrodynamics regime, due to the morphological changes at tidal ebb (1st row) and flood (2nd row) phases. The color bar ranges for η were capped to match the original work. During the flood tide, the hydrodynamic patterns show strong qualitative agreement. Key features, such as the sea surface elevation and the formation of eddies, both inside the lagoon and along the exterior of the inlet walls, correspond well with the FVCOM results (indicated by arrows). SHYFEM-MPI captures similar hydrostatic setup and setdown across the inlet throat. These localized anomalies in free-surface height arise from the combined influence of the tidal pressure field and spatial gradients in wave radiation stresses introduced through the coupled wave–current momentum fluxes. The resultant setdown on the lagoon side and setup on the sloping side (north) reflect the redistribution of wave-induced momentum and the associated modification of the quasi-hydrostatic balance within the inlet, consistent with the mechanisms discussed for an inlet domain in Chapter 2 (Causio et al. (2025)). A similar correspondence is observed for the external eddies during the ebb tide. However, a discrepancy is noted within the lagoon during the ebb phase, where SHYFEM-MPI predicts eddy formations that are absent in the FVCOM simulation. This mismatch most likely arises from differences in numerical diffusion between the models: SHYFEM’s finite-element discretization retains smaller-scale vorticity, whereas FVCOM’s finite-volume scheme introduces greater numerical dissipation, leading to smoother flow fields and suppressed eddy activity.

For a quantitative inter-model comparison, the SHYFEM-MPI results were benchmarked against the Thetis ocean model (Kärnä et al., 2018), which utilizes a discontinuous Galerkin finite element scheme. To ensure a robust comparison, the models were configured with identical setups. Both simulations used the same unstructured grid and were forced by a semi-diurnal tidal signal with a 4-hour smooth ramp-up period. Key physical parameterizations were also harmonized, including the adoption of a quadratic drag coefficient for bottom friction and

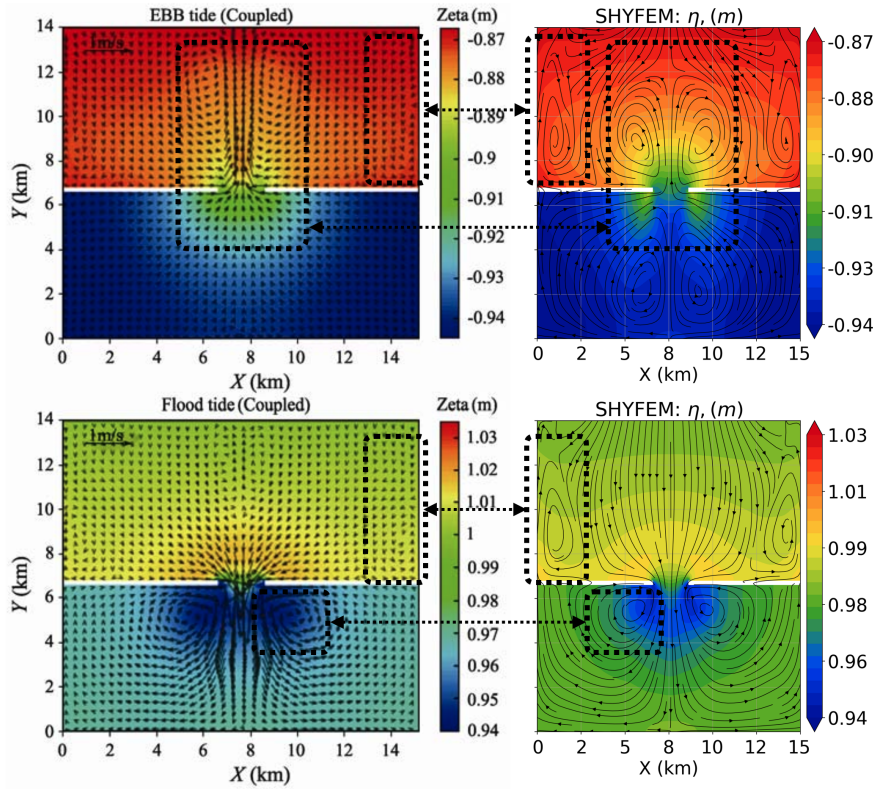


Figure 4.3.3. Ebb and flood tide phases: sea surface elevation (η) and current vectors $\mathbf{u}$ comparisons between SHYFEM-MPI (right) and FVCOM (left) adapted from Wu et al. (2011). The dashed boxes indicate eddy formations corresponding between the two models.

equivalent horizontal viscosity values. The results are shown in Figure 4.3.4 for the velocity field, suspended sediment concentration, bed elevation, and sea surface elevation. Both models demonstrate a strong agreement in simulating the hydrodynamics and sediment transport fields. The velocity fields (first column) capture the formation of a strong flood jet entering the lagoon, with the lateral eddies on the northern side. The high correlation coefficient ($r = 0.96$) in the difference plot attests to the similarity in flow patterns, with a low RMSE of 0.03 m/s and a bias of 0.006 m/s. Although, the effects of the discontinuous Galerkin scheme in Thetis are evident near the inlet walls, where the velocity gradients are sharper with the formation of stronger eddies,

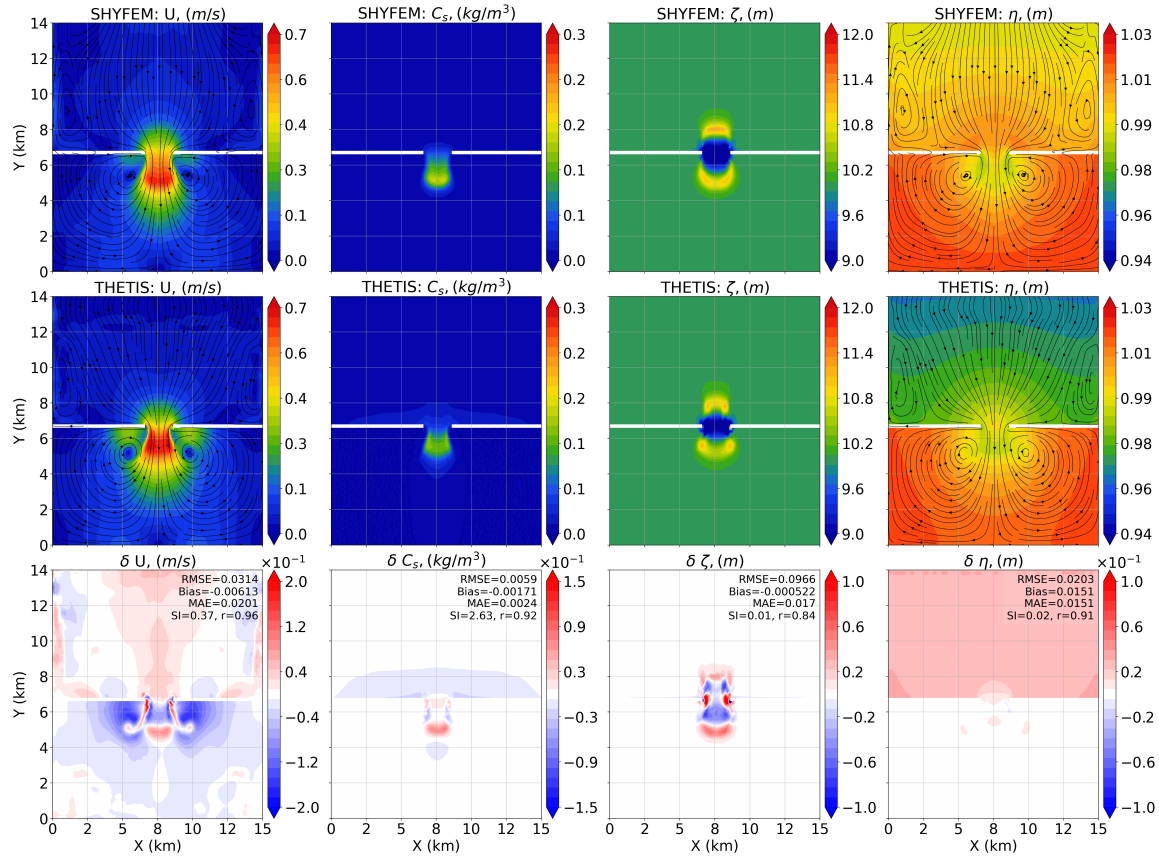


Figure 4.3.4. Thetis model comparison: velocity field (U), suspended sediment concentration (C_s), bed elevation (ζ), and sea surface elevation (η). The last row provides differences between the two models and the statistical metrics.

as seen in blue on the difference plot. Similarly, both models capture the jet-driven SSC profiles (second column) with a high correlation ($r = 0.92$). A distinct plume of suspended sediment is shown originating from the inlet, where high bed shear stress entrains sediments, which are then advected into the basin. The morphological discrepancies (third column) are slightly more pronounced between the two models, as previously noted, due to differences in numerical schemes. This is particularly evident near the eastern inlet wall, where Thetis predicts a deposition lobe that is absent in SHYFEM-MPI, which contributes to the lower correlation ($r = 0.84$). This ef-

fect at the inlet wall can be effectively mitigated by increasing the grid resolution around the inlet area. Nevertheless, the overall patterns remain similar and resemble the inlet bed evolution described by Warner et al. (2008) and Wu et al. (2011), with the characteristic radial and flank erosion–deposition forms discussed earlier. The sea surface elevation fields (fourth column) are in good agreement, with a high correlation ($r = 0.91$), particularly within the lagoon with a maximum difference of <1 cm. The discrepancies are more pronounced outside the lagoon over the sloping bathymetry, where SHYFEM-MPI predicts a slightly higher setup, with the overall RMSE of 0.02 m and a bias of 0.01 m.

Figure 4.3.5 illustrates the temporal evolution of suspended sediment concentration (SSC) and bed morphology along the main inlet transect (see Figure 4.3.1). The snapshots are shown for the initial phase, the first 10h (top row), and the final phase (bottom row, from 38h to 48h) of the simulation. The transport dynamics are tightly coupled to the semi-diurnal tidal cycle, which is driven by the pressure gradient between the open boundary and the lagoon. During the flood tide, the higher water level at the open boundary drives flow into the lagoon (e.g. at 15m, 10h, 45h). This generates high bed shear stresses at the inlet, entraining sediment and advecting them into the basin. As the flow decelerates within the lagoon, and the free surface equilibrium is reached, sediment is deposited, contributing to the formation of a flood-tidal delta (e.g. 2.5h and 48h). Conversely, during the ebb tide (e.g., $t = 5h$ and $t = 38h$), the hydraulic gradient reverses, and flow is directed out of the lagoon. This process scours the bed on the lagoon side of the inlet and ejects a sediment plume offshore, leading to the development of an ebb-tidal delta ($t = 42.5h$). Over multiple tidal cycles, this alternating transport results in the progressive erosion of the inlet crest and the growth of depositional features on both the lagoon and seaward sides, as seen in the evolution from the initial (dashed line) to the final (solid line) bed profile. The concentration of SSC is highest during peak ebb and flood flows, confirming that sediment mobilization is directly linked to the periods of maximum hydrodynamic forcing.

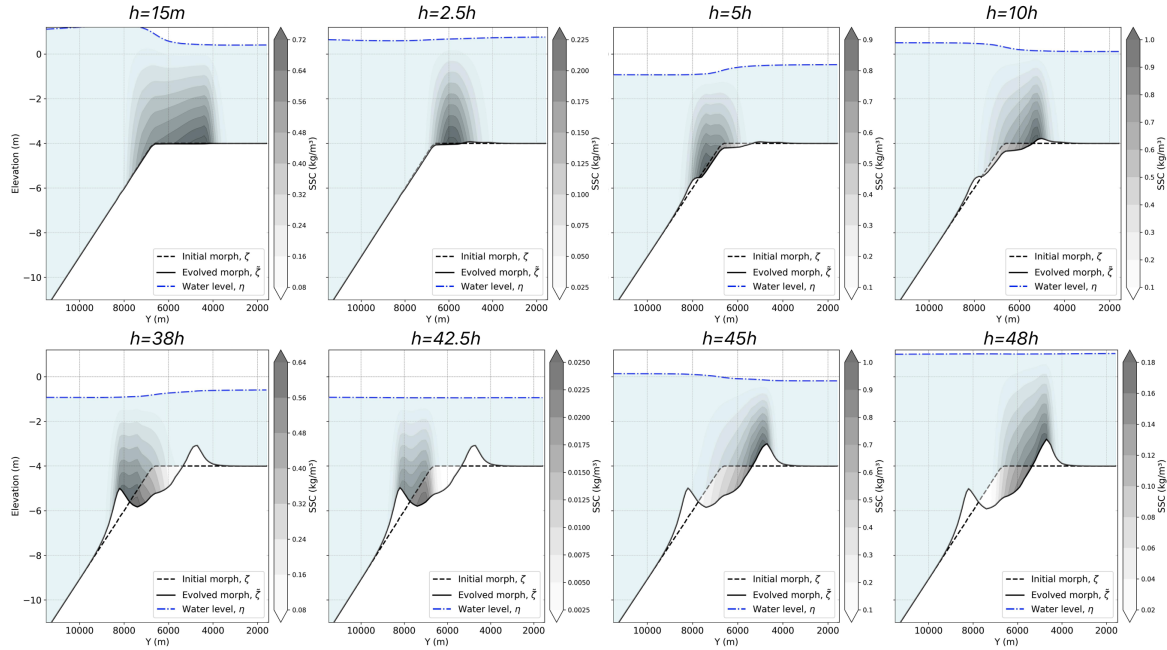


Figure 4.3.5. Suspended sediment concentration (SSC) profiles at along the A-B transect (see Figure 4.3.1). The blue dash-dotted line indicates the free surface elevation. The solid black line indicates the evolved bed elevation at an indicated hour, and the dashed black line the initial bed elevation for the reference.

As configured in Section 4.2.2.3 to include feedbacks between hydrodynamics and morphodynamics, the model reveals the effects of morphological changes ($\partial\zeta/\partial t$) on sea surface elevation and currents, as shown in Figure 4.3.6. We run two 48 hour simulations in SHYFEM-MPI with and without the feedback loop, and compare the two experiments at the ebb (left) and flood (right) tides. This feedback mechanism, where the morphodynamics module updates the bed elevation at each internal timestep subsequently solving the hydrodynamics, ensures a seamless and a hard-coupled interaction between the two processes, allowing for a continuous and dynamic exchange of information that captures the evolving system behavior. The variation in η is on the order of 10^{-3} m, reaching 5 mm during the ebb and flood tides. The impact on the free-surface elevation is most pronounced around areas of bed deformation, indicating a stronger

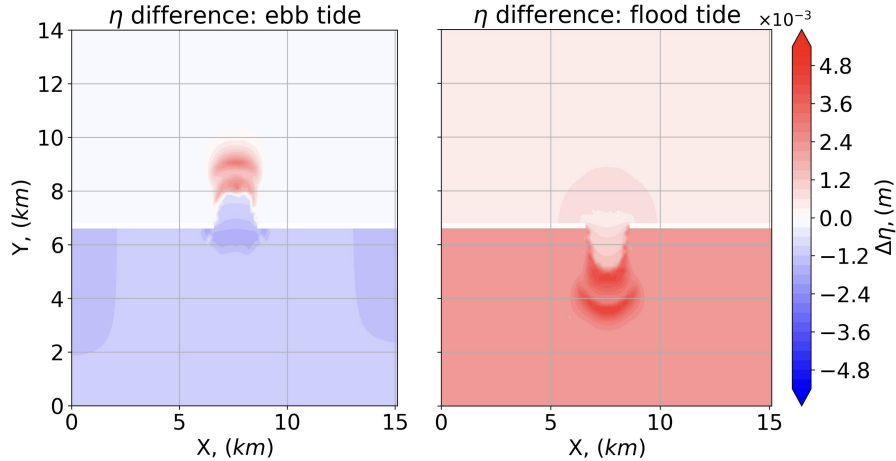


Figure 4.3.6. Sea surface elevation (η) differences between the two experiments with and without feedback from morphodynamics at ebb (left) and flood (right) tides, given by the bed elevation change ($\partial\zeta/\partial t$) component in Eq. 4.2.8.

influence on the lagoon side of the inlet during flood tide, where the elevation remains consistently higher. Although the differences are small, they reflect the dynamic interaction between the evolving bed and the hydrodynamics, which can amplify coastal impacts and potentially lead to higher local erosion rates or flooding risks over extended timescales.

4.3.2 River channel

To evaluate the model's performance in a purely current-driven fluvial environment, we simulate morphodynamic evolution in an idealized river meander, following the experiments of Yen and Lee (1995). Due to the sea-level-referenced free surface formulation of SHYFEM-MPI, this test case is intended as a qualitative, process-oriented benchmark focusing on erosion–deposition patterns and secondary flow effects, rather than a fully quantitative reproduction of laboratory water levels and bed evolution amplitudes. River meanders represent one of the most fundamental forms of alluvial morphology, characterized by alternating bends that induce secondary circulation and complex patterns of sediment transport. The spatial distribution

of shear stress and velocity within a bend typically leads to sediment deposition along the inner bank, where flow velocities and bed shear stresses are relatively low, and to pronounced erosion along the outer bank, where flow acceleration enhances sediment entrainment (Tassi et al., 2023). The continuous interaction between these depositional and erosional processes governs channel migration and meander evolution over time. A correct representation of flow curvature effects and sediment feedbacks is crucial, especially when extending model applications to the river-estuary-coastal continuum. Recent work by Clare et al. (2021) successfully reproduced the Yen and Lee (1995) experiments using the Thetis model, demonstrating the ability of a depth-averaged hydrodynamic-sediment transport framework to capture the essential morphodynamic features of a meandering channel. Building upon this, the present study aims to replicate the same benchmark scenario with the SHYFEM-MPI model, in order to evaluate its capacity to reproduce the characteristic erosion and deposition zones within a river bend.

4.3.2.1 River domain and model set-up

Figure 4.3.7 shows the computational domain, with a few results from the laboratory experiments, to illustrate the typical erosion and deposition patterns in a river bend. Following similar set-up as in Clare et al. (2021), and an identical domain and grid resolution of 0.1 m , we run the SHYFEM-MPI model for 5 h , with an influx rate of $0.02\text{ m}^3/\text{s}$ linearly growing through $t = 100\text{ m}$, reaching the maximum rate of $0.053\text{ m}^3/\text{s}$, and then decreasing to $0.02\text{ m}^3/\text{s}$ toward $t = 5\text{ h}$. The water depth is set to vary from approx. 0.05 m to 0.1 m . The complete set of parameters is summarized in Table 4.3.2.

4.3.2.2 River results and inter-model comparison

Figure 4.3.8 presents the spatial distribution of the scaled bed elevation changes ($\Delta\zeta/\zeta$) at the end of the simulation for both Thetis (left) and SHYFEM-MPI (right). The color scale represents the normalized morphological evolution, where positive values indicate sediment

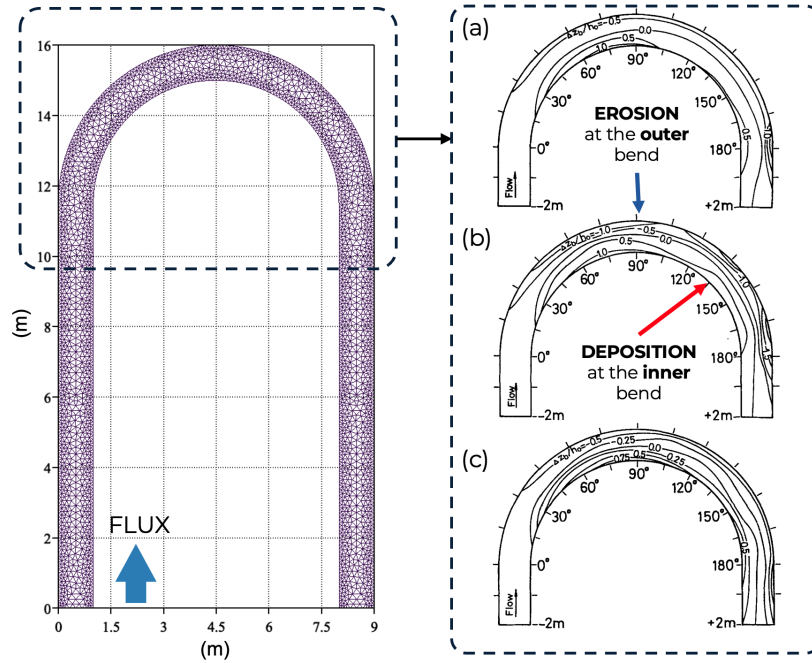
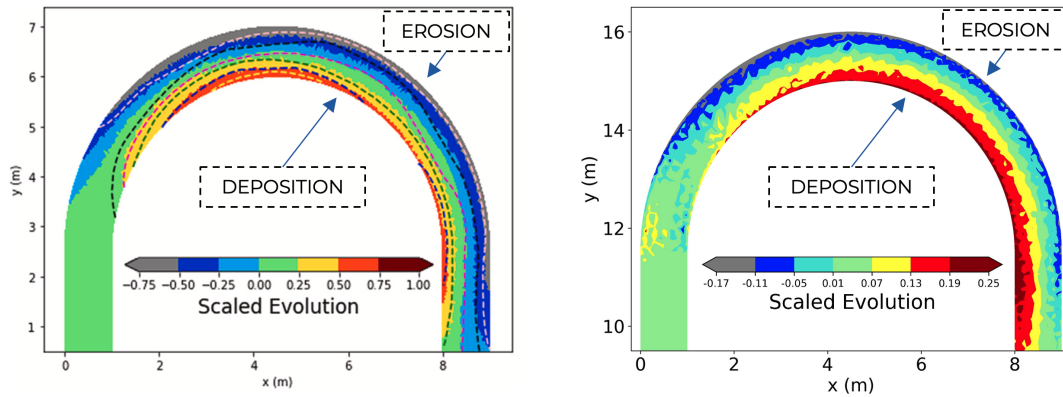


Figure 4.3.7. River bend domain with the arrow indicating the flow direction. On the right side are a few experimental (a,b,c) results of Yen and Lee (1995), showing the erosion and deposition patterns, in terms of scaled bed elevation changes ($\Delta\zeta/\zeta$).

deposition and negative values denote erosion. Both models reproduce the characteristic morphological signature of a meandering channel, sediment deposition along the inner (concave) bank, and erosion concentrated on the outer (convex) bank of the bend. These patterns arise from the curvature-induced secondary flow that develops within the bend, generating a helical motion that transports high-momentum near-surface flow toward the outer bank while directing near-bed sediment toward the inner bank. The resulting imbalance in bed shear stress and sediment transport rate gives rise to distinct zones of lateral erosion and deposition that shape the overall meander morphology. The SHYFEM-MPI results exhibit a coherent reproduction of these expected morphodynamic trends, showing a clear depositional zone at the inner bank and an erosional front along the outer curvature, in good qualitative agreement with the Thetis sim-

Table 4.3.2. Parameter values for the meander test case. Source: Clare et al. (2021).

Variable name	Value
Channel width	1 m
Inner radius	3.5 m
Outer radius	4.5 m
Straight reach at channel ends	11.5 m
Morphological simulation time	5 h
Depth	$\approx 0.05 - 0.1$ m
Median particle size (d_{50})	1×10^{-3} m
Sediment density (ρ_s)	2650 kg m^{-3}
Water density (ρ_f)	1000 kg m^{-3}
Kinematic viscosity (ν)	$0.01 \text{ m}^2 \text{ s}^{-1}$
Bed sediment porosity (p')	0.4
Longitudinal bed slope	0.0035 m

**Figure 4.3.8.** Scaled bed elevation changes ($\Delta\zeta/\zeta$) with the slope and secondary currents corrections at $t = 5$ h of the simulation for the Thetis (left) and SHYFEM-MPI (right) models.

ulation and with the laboratory observations of Yen and Lee (1995). However, the amplitude of bed level changes is comparatively lower in SHYFEM-MPI than in Thetis, likely due to differences in bed friction factorization; quantitatively, this is reflected in a narrower range of scaled elevation changes, indicating that SHYFEM-MPI underestimates both erosion and deposition

magnitudes. This discrepancy also stems from the sensitivity of sediment transport dynamics to longitudinal bed slope and free-surface elevation adjustments, as noted by Clare et al. (2021). Accurately reproducing such fine-scale experimental results requires careful calibration and fine-tuning of these parameters, which lies beyond the scope of the present benchmark analysis.

In Figure 4.3.9, we illustrate the effect of including the secondary flow correction terms, represented by Eqs. 4.2.42, 4.2.43, 4.2.44, on morphological evolution, by running two simulations without (a) and with (b) the secondary flow effects. The comparison clearly demonstrates that

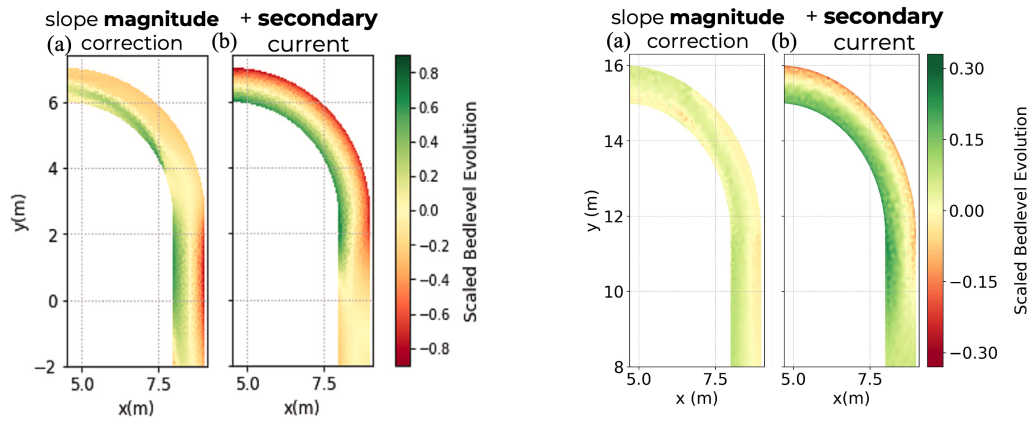


Figure 4.3.9. Scaled bed elevation changes ($\Delta\zeta/\zeta$) at the end of the simulation without (a) and with (b) secondary flow effects. Right panel shows the results of Thetis model and the left panel the SHYFEM-MPI results.

incorporating secondary flow effects significantly enhances the realism of the morphodynamic response within the meander bend. Without the inclusion of the helical flow (panel a), both Thetis (left) and SHYFEM-MPI (right) models predict a pattern of bed level change with erosion and deposition confined to a narrow band near, reflecting the dominance of the primary flow field, where lateral momentum exchange is insufficient to generate the transverse sediment redistribution typically observed in natural curved channels. When the secondary flow parameterization is activated (panel b), the morphodynamic pattern becomes asymmetric, with a distinct lateral separation between erosional and depositional zones, where the outer bank

experiences enhanced erosion, while deposition intensifies along the inner bank. This mechanism redirects near-bed sediment toward the inner bank and deepens the outer-bank scour. As observed earlier, the magnitudes of bed level changes remain lower in SHYFEM-MPI compared to Thetis, that can be further mitigated through model calibration, such as longitudinal bed slope and adjusting the morphological factor, as well as the grid resolution to account for the difference that can emerge due to the different numerical schemes used in the two models.

The apparent oscillations visible in the SHYFEM-MPI bed elevation field (Figure 4.3.8, right) reflect a combination of physical and numerical factors. Primarily, the reduced magnitude of predicted bed evolution in SHYFEM-MPI compared to Thetis compresses the dynamic range, amplifying the visibility of small-scale perturbations in the color scaling. Additionally, the two models employ distinct velocity discretizations, SHYFEM-MPI uses piecewise constant (P0) elements for the velocity field, whereas Thetis employs piecewise linear (P1) basis functions. This higher-order spatial representation in Thetis produces smoother velocity gradients and consequently smoother morphodynamic response within each element. These differences in numerical approximation are not deficiencies but reflect inherent trade-offs between computational efficiency (P0) and spatial smoothness (P1).

Despite the quantitative differences, the overall morphodynamic patterns predicted by the implemented model exhibit high similarity with both the Thetis model and the experimental results. The accurate reproduction of the characteristic depositional and erosional zones indicates that the model successfully captures the key feedbacks between flow curvature, secondary circulation, and sediment redistribution that control meander evolution.

4.3.3 Fiumicino case study

To assess the development on a realistic coastal environment, we construct case study for the Fiumicino coastline, where the Tiber River discharges into the Tyrrhenian Sea, Italy. This area is characterized by a complex interplay of tidal, wave and riverine processes. The hydrodynamics

of the region were recently investigated by Bonamano et al. (2024) using the SHYFEM-MPI model, with emphasis on the river-coast-ocean continuum, and the impact of river discharge in modulating nearshore circulation. Fiumicino coastal region is particularly well suited for model testing and validation due to the availability of extensive observational datasets, including both in-situ monitoring and high-resolution satellite remote sensing products. These datasets allow for a calibrated set-up of the numerical simulations and a quantitative assessment of model performance, especially in reproducing suspended sediment concentration patterns governed by a wave-current-river combined action.

4.3.3.1 Data collection and processing

The morphodynamic setting is controlled by variable river discharge and sediment supply from the Tiber, a predominantly southwesterly to westerly (SW–W) wave climate with episodic energetic storm events (Shirinov et al., 2025), and local coastal circulation processes that drive sediment transport alongshore and offshore (Iacono et al., 2021; Astraldi and Gasparini, 1994). The river discharge data is obtained from the Ripetta gauging station, located 38 km upstream of the river mouth for the entire period of simulation. It should be noted that the discharge time series were not shifted to account for flood-wave travel time between the Ripetta station and the river mouth. While this reach is hydrologically active and receives lateral water and sediment inputs, spectral and cross-correlation analyses did not reveal a consistent, event-independent phase lag in the discharge signal. Consequently, to avoid introducing ad hoc timing adjustments, the forcing was applied without a fixed temporal shift, as propagation effects could not be resolved at the temporal resolution of the available data.

To characterize sediment properties near and downstream of the river mouth, we employed satellite-derived estimates of suspended particulate matter and grain-size distributions (GSD). Sentinel-2 imagery was processed using the C2RCC (Case-2 Regional CoastColour) algorithm (Soriano-González et al., 2022), which applies atmospheric and water-column corrections to

retrieve total suspended sediment concentrations from backscattering coefficients. Following the work of Pitarch et al. (2019), we identify four sediment classes, varying from coarse silt to coarse sand, with diameters of 0.030, 0.062, 0.093, 0.125 mm and corresponding fractional contributions of 0.10, 0.40, 0.30, 0.20, respectively, discharged from the river mouth. However, the flocculation processes are not considered in this study, hence, the small silt fractions are treated as non-cohesive sediments. The SSC at the river delta is computed using quadratic formulation described in Jung et al. (2020) and depicted in Figure 4.3.10a. The empirical coefficients (c_1 , c_2 , c_3) were calibrated against in-situ measurements following Iadanza and Napolitano (2006). The bed morphology (Figure 4.3.10b) was constrained using field observations and reflects a

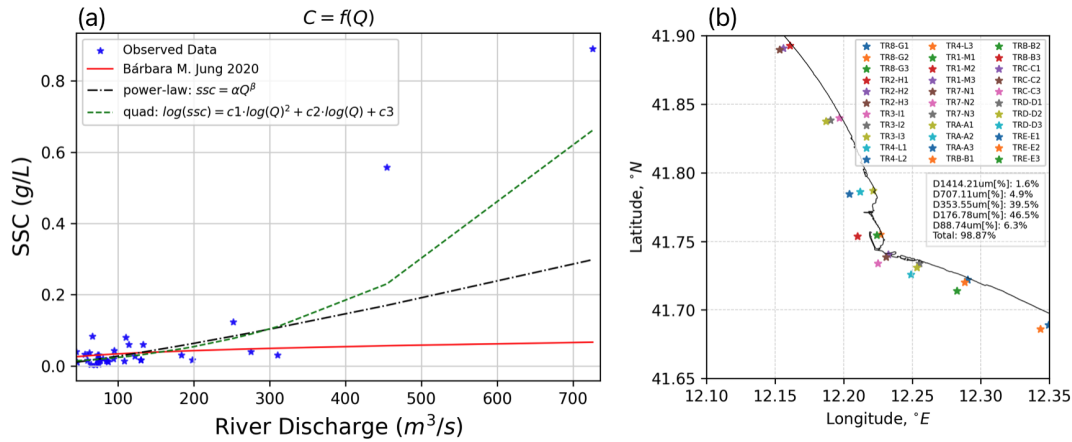


Figure 4.3.10. (a) Suspended sediment concentration (SSC), and (b) grain size distribution (GSD) at the Tiber river mouth. The quadratic formulation used to compute SSC is based on in-situ measurements and is depicted in panel (a), along with conventionally used power-law formulations for comparison. The panel (b) shows the GSD sampling tracks during field campaigns, while the fractions of different sediment classes composing the bed morphology is given in terms of their sizes and corresponding averages over the sampling tracks (second box).

distinct sediment composition relative to the riverine input. The fractions of different sediment classes composing the bed morphology is applied as depicted in the figure (b), although, only four classes were rebuilt in the simulation, excluding very coarse sand $D = 1414.21 \mu m$, which accounts for only 1% of the total bed composition.

4.3.3.2 Model setup

The domain is discretized using an unstructured grid designed to capture both nearshore and offshore dynamics, with spatial resolution ranging from approximately 40 m along the coast and river mouth to 1.8 km in the open sea. Hydrodynamic and wave simulations are forced with meteorological fields from the ECMWF analysis dataset (Owens and Hewson, 2018), available at 10 km spatial resolution and 6-hour temporal frequency. Surface meteorological parameters are corrected along the coastal zone using the sea-over-land adjustment procedure of Kara et al. (2008) to improve the representation of land–sea gradients. The circulation model is driven by 2 m air temperature, 2 m dew-point temperature, mean sea-level pressure, total precipitation, and 10 m zonal and meridional wind components. Scalar fields are imposed through clamped boundary conditions, while velocity components are nudged toward external solutions using a relaxation time of 3600 s, following the approach described in Section 2.4.

Open lateral boundaries are prescribed using outputs from the CMEMS regional model, downscaled to 1-hour temporal resolution. The simulation covers a continuous 10-month period (1 August 2020 – 1 June 2021) for the available forcing fields, ensuring the inclusion of seasonal variability in river discharge, wind forcing, and wave climate.

The bathymetry is derived through variational analysis using the DIVAnd tool (Barth et al. (2014)), combining in-situ radar measurements with background data from the EMODnet Digital Terrain Model (Consortium, 2016). The error covariance fields are precomputed based on instrument uncertainty and standard deviation estimates provided by EMODnet. All geospatial datasets are projected onto the WGS84 horizontal reference system (longitude–latitude) and referenced to the mean sea level (MSL) vertical datum for consistency across model components.

Figure 4.3.11 illustrates the modelling domain at Tiber river mouth, including the bathymetry map, and an unstructured grid. Waves are provided offline to the circulation–sediment core at the frequency of 1h, and linearly interpolated in time to match the circulation model time step. Wave forcing fields follow the methodology described in Section 4.2. The bed roughness

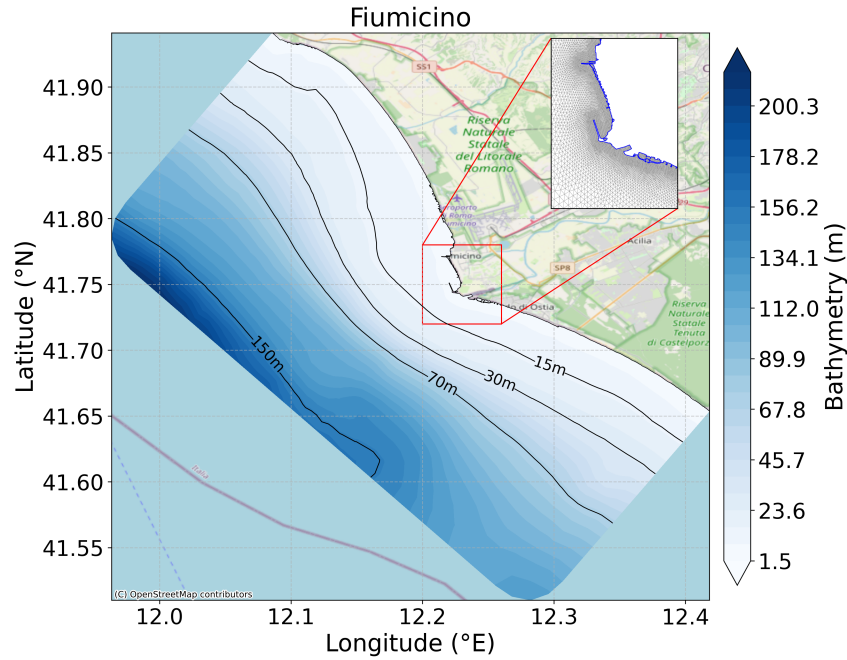


Figure 4.3.11. Fiumicino model domain, bathymetry and unstructured grid (top-right framed box). The isobars indicate the depth.

is computed using a unified formulation for bedform of Van Rijn (2007), and the intra-wave bedload transport is activated as in Eq. 4.2.38. The universal sediment fall velocity formulation, Eq. 4.2.15, is used.

4.3.3.3 Validation against satellite-derived suspended sediments

The performance of the sediment transport model was validated against satellite-derived observations for a high river discharge event on 14 February 2021. Modelled SSC was compared with Total Suspended Matter (TSM) retrieved from Sentinel-2 imagery using the C2RCC processor. The comparison, synchronized to the satellite overpass time (10:00h CET), focused on both the spatial plume morphology and quantitative concentration profiles.

Figure 4.3.12a presents a side-by-side comparison of the model output and the satellite observation. A qualitative assessment of the spatial maps (top row) reveals that the model successfully reproduces the primary features of the sediment dispersal pattern. It correctly identifies the two distinct river plumes originating from the Fiumara Grande and Fiumara Piccola, capturing the presence of a nearshore zone of higher concentration north of the Fiumara Piccola, which is attributable to wave-induced sediment resuspension. However, notable discrepancies in the plume morphology are apparent. The modelled plumes appear narrower and more confined to the near-field, with steeper concentration gradients, whereas the satellite imagery shows broader, more diffuse plumes extending further offshore.

A quantitative analysis based on transects extending from each river mouth (Figure 4.3.12, middle and bottom rows) reveals the differences in SSC distribution between the model and satellite data. provides further insight. While the model correctly simulates the peak concentration in the immediate vicinity of the river mouths and the general offshore decay trend, a systematic underestimation of SSC by the model is evident, particularly in the distal regions of the plumes (beyond 1 km offshore). This is quantitatively confirmed by the negative bias values for both the Fiumara Grande (BIAS = -0.185 kg/m^3) and Fiumara Piccola (BIAS = -0.084 kg/m^3) transects. The model exhibits a more rapid decline in concentration compared to the satellite data, which maintains higher TSM values further from the source.

These discrepancies likely stem from several simplifications within the model's configuration. A primary contributing factor is the model's sediment characterization, which does not account for the cohesive nature of fine-grained sediments (silt and clay). In reality, these particles can flocculate, altering their settling velocities, or remain in suspension for extended periods as wash load. The model's treatment of all sediments as non-cohesive likely leads to excessive deposition in the near-field and fails to capture the long-distance transport of the finest fractions, resulting in the observed offshore underestimation. In addition, the use of a restricted number of sediment classes may not adequately represent the full grain-size distribution of the

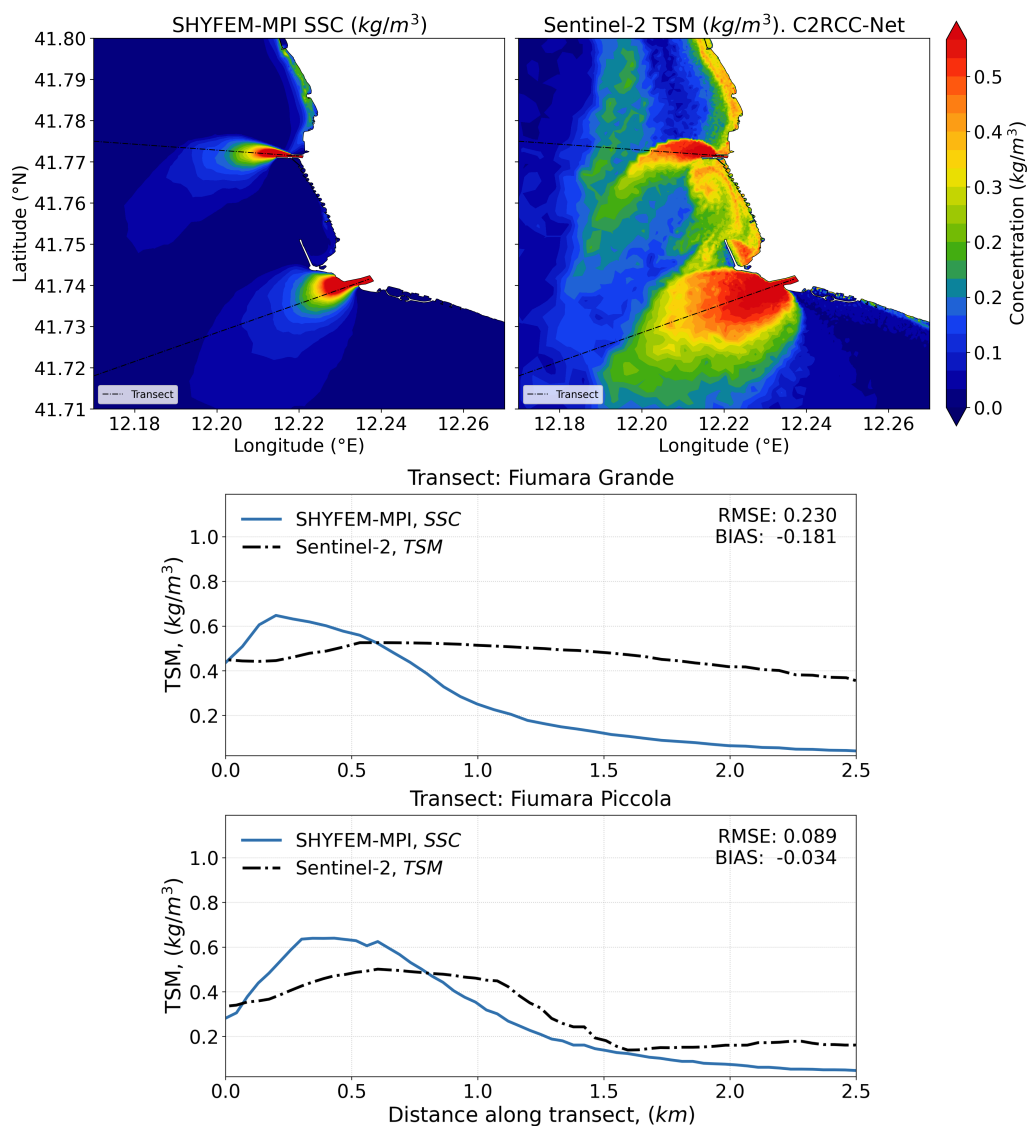


Figure 4.3.12. Comparison of modelled and satellite-derived suspended sediment concentration (SSC) on 14 February 2021 at 10:00 (CET). The first row shows the SSC maps near the Tiber river mouth for the model (left) and satellite (right). The second and third rows show the SSC transect profiles extending from the two river mouths to the offshore area.

riverine sediment load, further limiting the model's ability to simulate the differential transport of various particle sizes. Nevertheless, the model effectively captures the primary dynamics of sediment dispersal driven by river discharge and wave action.

Figure 4.3.13 displays the vertical structure of the simulated river plumes through cross-sections of suspended sediments and velocity components along the two transects. The SSC profiles (top row) clearly show that the sediment is concentrated within the upper 2-4 meters of the water column. Concentrations are highest near the river mouths and decrease with both depth and distance offshore. This vertical distribution is characteristic of a hypopycnal plume, where the buoyant, sediment-laden freshwater discharged by the river flows out over the denser, saline coastal water (Yankovsky and Chapman, 1997). The resulting density stratification establishes a sharp pycnocline that inhibits vertical mixing, effectively trapping the suspended sediment in the surface layer. The velocity profiles provide crucial insight into the plume's dynamics. The zonal velocity component (u , middle row) reveals a classic two-layer estuarine circulation. A strong, seaward-directed outflow is evident in the upper layer (0-4 m deep). Beneath this surface jet, a weaker, compensating landward flow is established, driven by the baroclinic pressure gradient. The landward flow is less pronounced in the Fiumara Piccola transect, likely due to the influence of the extended seaward concrete structure along the plume path, which modifies the local circulation patterns.

The meridional velocity component (v , bottom row) governs the alongshore transport. The profiles for both river mouths, particularly Fiumara Grande, show a dominant southward velocity (negative values). This indicates that upon exiting the river mouth, the plume is immediately advected by a prevailing southward coastal current, also evident in Figure 4.3.12 (top row), as plumes tend to divert southward along the coast. However, due to the concrete wall along the Fiumara Piccola, the surface flow is reflected northward near the mouth.

By combining these velocity components, a comprehensive 3D trajectory emerges: the river discharge flows offshore as a buoyant jet and is concurrently bent southward. The model, there-

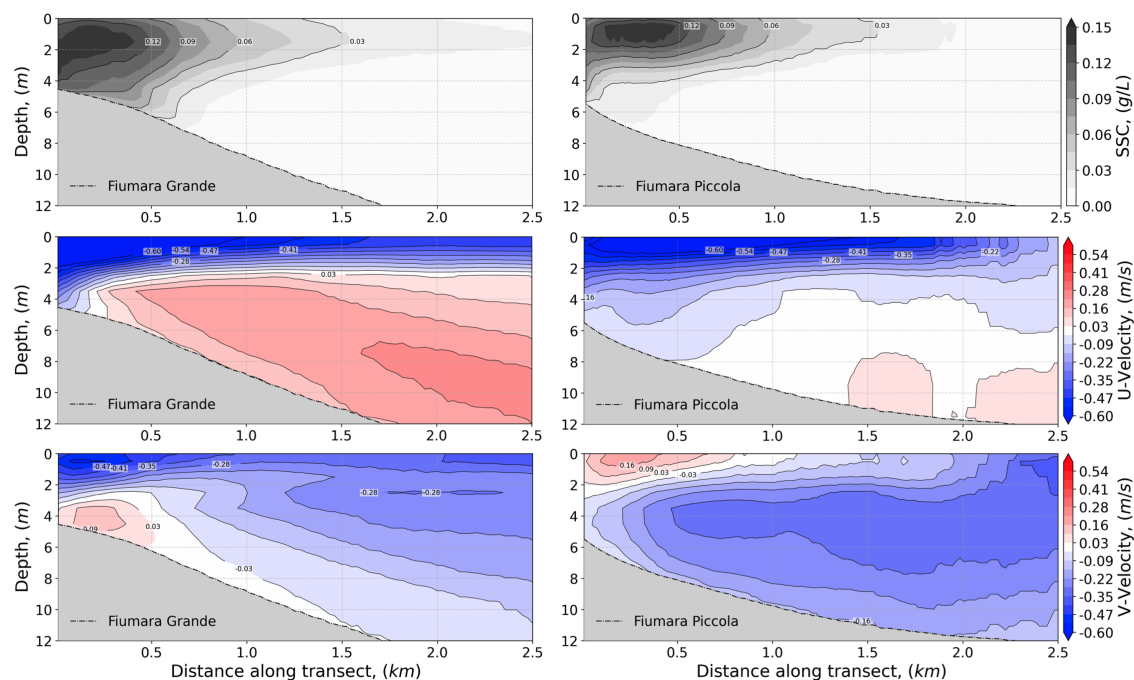


Figure 4.3.13. Vertical profiles of suspended sediment concentration (SSC) at two locations along the transect lines on 14 February 2021. The second and third rows depict the zonal (U) and meridional (V) velocity components.

fore, successfully captures the key hydrodynamic processes controlling the plume's path, from its initial vertical stratification to its subsequent offshore and alongshore dispersal.

4.3.3.4 Comparison with the CTD casts

For a more rigorous, multi-seasonal validation, modelled SSC profiles were compared against in-situ data from CTD casts collected during several field campaigns in various seasons between Summer 2020 and Spring 2021. The results, presented in Figure 4.3.14, reveal a pronounced spatial bias in the model's performance. A consistent overestimation of SSC is observed at nearshore stations, located in the direct vicinity of the river mouths. This discrepancy is likely a direct consequence of the model's boundary conditions. The river discharge and sediment

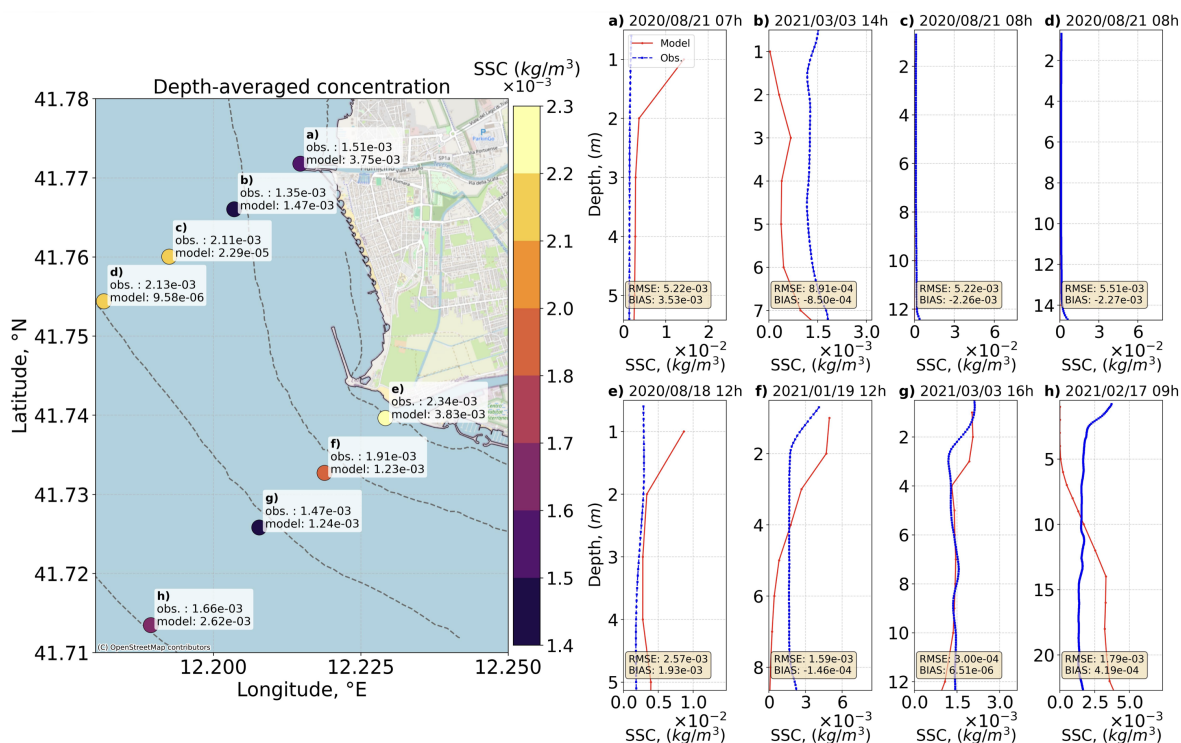


Figure 4.3.14. Comparison of modelled and measured suspended sediment concentration (SSC) profiles from CTD casts at various stations. The map illustrates the spacial distribution of CTD stations (left), with the modelled and measured SSC values indicated by the color scale, and summarised in the annotation boxes. The vertical profiles of SSC (right) compare the model (red) with CTD measurements (blue) at each corresponding station. The statistical metrics are provided for each station.

load were prescribed using data from the Ripietta gauging station, situated 38 km upstream. This approach neglects the significant sediment deposition and trapping (estimated from the discharge rates) that naturally occurs within the lower reaches and estuary of the river system, leading to an artificially inflated sediment flux being introduced into the coastal model at the river mouths. Conversely, and in agreement with the satellite data comparison, the model tends to underestimate SSC at stations further offshore across the seasons. This highlights the model's limitations in simulating the far-field plume. The primary reasons remain the absence of very fine, slow-settling sediment classes that constitute the bulk of the distal plume, and the neglect

of cohesive sediment dynamics such as flocculation, which influences particle aggregation and transport pathways.

Despite these discrepancies in magnitude, the model captures the general shape of the vertical SSC profiles with reasonable fidelity, often replicating the surface-advected nature of the plume (nearshore). This suggests that the underlying hydrodynamics, such as stratification, are simulated plausibly. The Fiumara Grande (southern branch) shows a better agreement with the CTD measurements in general. The model performance shows a good correlation throughout the seasons with the bias ranging from 10^{-6} to 10^{-3} kg/m^3 and RMSE from 10^{-4} to 10^{-3} kg/m^3 . This indicates that, with appropriate calibration of the discharge rates and suspended sediment concentrations at the river mouths and within the domain, supported by local observations, and with the application of the non-zero gradient boundary conditions, model performance can be enhanced. Incorporating cohesive sediment dynamics and flocculation processes in future work would also improve model fidelity.

4.3.3.5 Physical drivers of seasonal sediment budget

Seasonal mean fields over the simulation period reveal a persistent river-driven surface plume whose spatial extent is strongly modulated by hydrodynamic forcing (Figure 4.3.15). Periods of reduced discharge and weaker wave activity (late summer–autumn and spring) exhibit relatively confined SSC patterns near the river mouth, whereas winter conditions show substantially elevated concentrations and enhanced offshore and alongshore spreading due to increased river input and wave-induced resuspension.

To characterize the hydrodynamic drivers underlying the seasonal SSC patterns observed in Figure 4.3.15, an Empirical Orthogonal Function (EOF) analysis was applied to bottom orbital velocities and surface currents (Figs. 4.3.17 and 4.3.18), with a complementary EOF decomposition of SSC (Fig. 4.3.16) to identify the dominant modes of sediment variability. The leading mode (EOF1) of bottom orbital velocity (Figure 4.3.17) explains over 90% of the variance, sug-

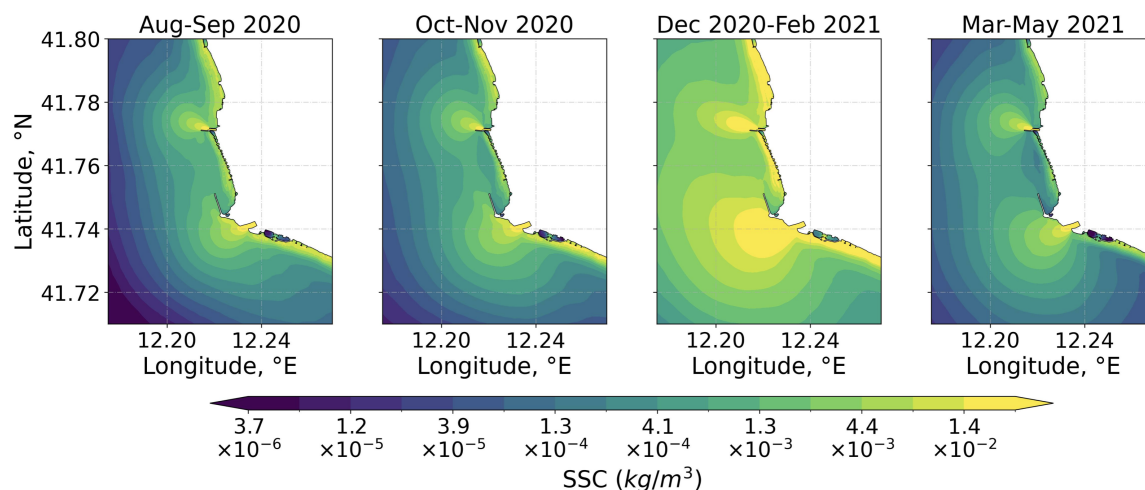


Figure 4.3.15. Seasonal mean suspended sediment concentration (SSC , kg/m^3) along the central Lazio coastline near the Tiber River mouth, averaged over late summer (Aug–Sep 2020), autumn (Oct–Nov 2020), winter (Dec 2020–Feb 2021), and spring (Mar–May 2021). The maps illustrate the seasonal variability in plume extent and dispersion under changing river discharge and hydrodynamic forcing.

gesting that wave-related near-bed hydrodynamic variability accounts for a large fraction of the seasonal signal along the shoreline. This mode intensifies during the winter months (Dec–Feb), corresponding to periods of higher near-bed wave action, which is consistent with the broader and more energetic SSC distributions observed in winter relative to the more localized plumes characteristic of summer conditions. Simultaneously, EOF1 of surface currents, accounting for 30–45% of variance (Figure 4.3.18), captures the dominant advective pathways. In winter, the strengthening of this mode facilitates the offshore and alongshore export of sediments, consistent with the local circulation patterns demonstrated by Vetrano et al. (2010). The second mode (EOF2) is associated with confined plume structures near the river mouths that dominate during calmer periods, leading to the sediment retention near the coastal region observed in the Aug–Sep and Oct–Nov averages.

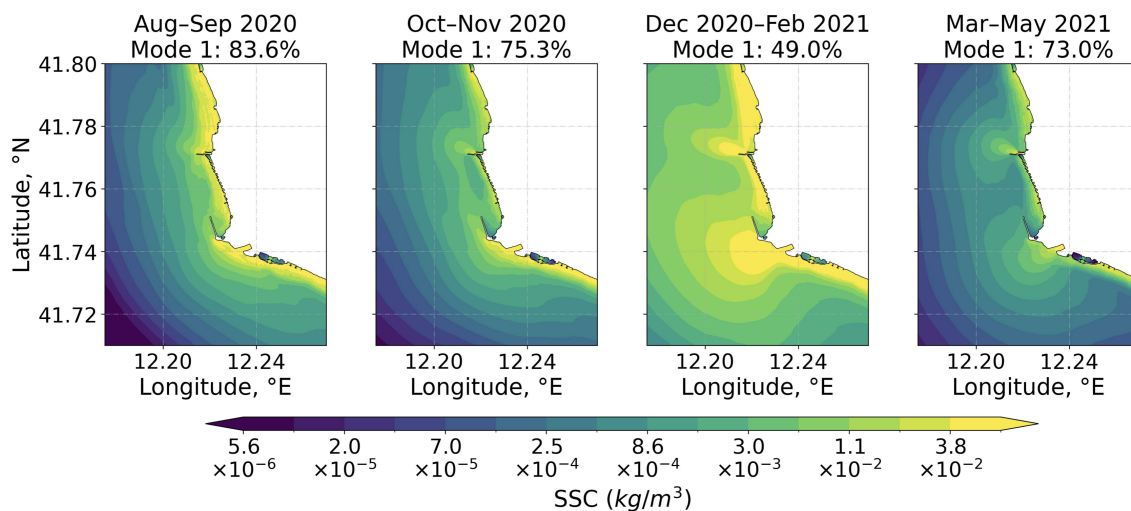


Figure 4.3.16. Empirical Orthogonal Function (EOF) analysis of suspended sediment concentration (SSC, kg/m^3) seasonal variability. The EOF1 mode explains 50–80% of the variance, representing the dominant seasonal pattern of sediment dispersal, with higher concentrations and broader plumes during winter months.

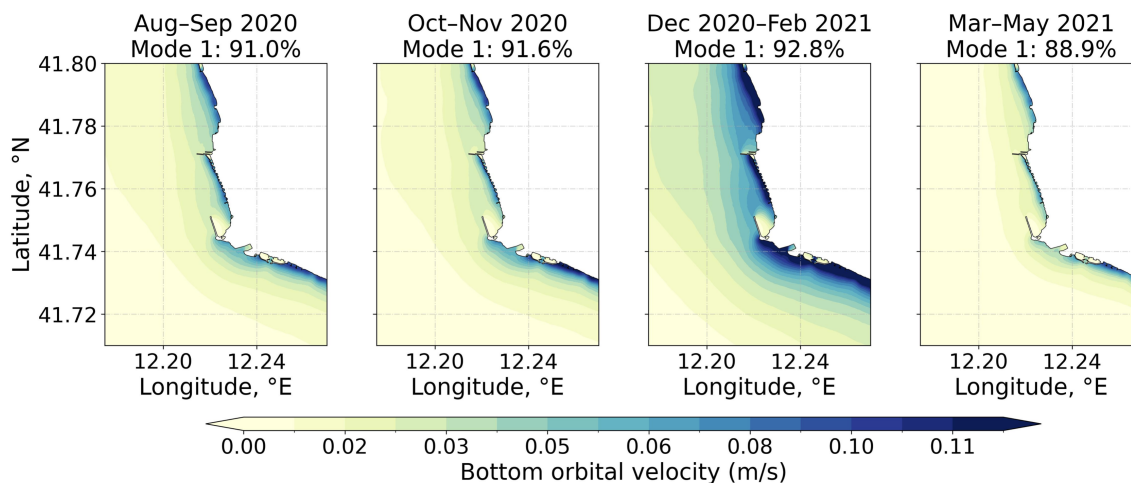


Figure 4.3.17. EOF analysis of bottom orbital velocities (m/s) across seasons. The leading mode (EOF1) explains over 90% of the total variance, representing a strongly coherent spatial pattern of wave-induced forcing for sediment resuspension.

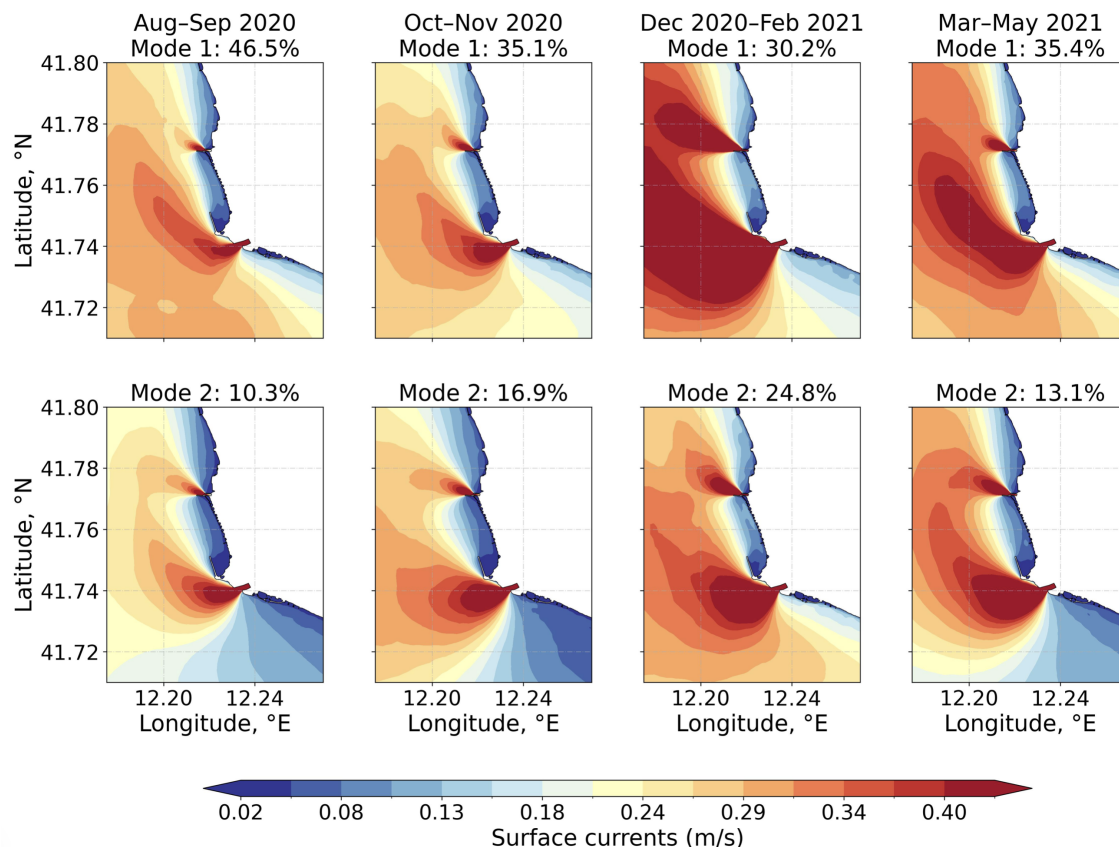


Figure 4.3.18. EOF analysis of surface currents (m/s) at the Tiber River delta. The top row illustrates the spatial distribution of the first mode (EOF1), explaining 30–46% of the variance; the bottom row illustrates the second mode (EOF2), explaining 10–25% of the variance.

Despite remaining quantitative biases associated with sediment boundary conditions and size-class representation (4.3.14), these results demonstrate that the SHYFEM-MPI STM framework effectively resolves the hydrodynamic coupling between wave-modulated near-bed sediment availability, through bottom orbital velocities, and current-induced advection and diffusion of the river plumes, indicating that the model captures the first-order mechanisms governing seasonal sediment dispersal.

4.4 Discussion

This chapter detailed the development, validation, and application of a three-dimensional, wave-forced sediment transport and morphodynamics model integrated within the SHYFEM-MPI unstructured-grid framework. The central objective was to construct a comprehensive numerical tool capable of simulating complex sediment and morphological dynamics across both idealized and real-world coastal and riverine environments. Key model enhancements included the integration of offline spectral wave forcing, the implementation of unified wave–current bedform and roughness parameterizations, intra-wave bedload transport, and a morphodynamic feedback mechanism linking bed evolution via the Exner equation to the free-surface elevation and circulation.

The model’s performance was first benchmarked against established idealized test cases. In the tidal inlet experiment, the model successfully reproduced the characteristic erosion and deposition patterns observed in previous studies with the state-of-the-art ROMS and FVCOM (Warner et al., 2008; Wu et al., 2011), demonstrating its ability to capture wave- and tide-driven morphodynamic response. An inter-model comparison with the coastal-ocean finite element model Thetis (Kärnä et al., 2018), using discontinuous Galerkin schemes, further confirmed the solution of the hydrodynamic and tracers fields with high correlation scores. For the river meander case, the model correctly simulated the expected erosion on the outer bank and deposition on the inner bank, consistent with laboratory experiments (Yen and Lee, 1995) and other numerical models (Clare et al., 2021; Tassi et al., 2023). This test highlighted the critical role of including secondary flow corrections to capture the three-dimensional nature of riverine transport.

Application to the complex domain of the Fiumicino coast, earlier investigated by Bonamano et al. (2024), demonstrated the model’s utility in a real-world setting. The model showed good qualitative and quantitative agreement with satellite-derived suspended sediment concentrations

during a high-discharge event, capturing the spatial extent and structure of the river plume. Comparisons with in-situ CTD casts confirmed the model's ability to represent vertical SSC profiles, although it revealed a tendency to overestimate concentrations near the river mouth and underestimate them offshore. These discrepancies highlight the challenges of accurately representing riverine boundary conditions, as forcing the model directly at the river mouth using upstream station data can introduce shifts in hydrodynamic response and sediment transport, whereas explicitly representing the river–sea continuum, as conducted by Bonamano et al. (2024), using the riverine morphodynamics established in 4.3.2, would likely improve both near-mouth and offshore sediment predictions. The combined analysis of EOF modes and seasonal SSC maps identify the dominant mechanisms governing the coastal sediment budget north and south of the river mouth, where unsheltered stretches of the coast are exposed to wave action, and current-driven advection regulates sediment redistribution, with surface currents transporting suspended material offshore.

Despite these achievements, several limitations must be acknowledged. The use of a z^* vertical coordinate system, while computationally efficient, can introduce numerical artifacts in morphodynamic simulations where steep bed slopes develop. The current one-way wave forcing neglects the potentially important feedback of evolving bathymetry on the wave field, a mechanism shown to be significant in the original works of Warner et al. (2008) and Wu et al. (2011). Furthermore, the model's exclusive treatment of non-cohesive sediment overlooks flocculation and aggregation processes that are critical for fine-grained sediment transport (Son and Hsu, 2011), thereby affecting settling velocities and dispersal patterns. Another limitation arises in the representation of the swash zone, which is characterized by highly unsteady, often bore-like uprush and backwash motions. These short-duration, non-hydrostatic flows are not resolved by phase-averaged spectral wave models, which rely on statistical representations of wave energy. Consequently, swash dynamics are typically incorporated through phase-resolving models that simulate the transformation of surface waves and shallow water flows in coastal wa-

ters (e.g., SWASH; Zijlema et al. (2011)). The morphological response within the swash zone results from a disequilibrium between the beachface gradient and temporal differences between uprush and backwash velocities, infiltration/exfiltration, and bore collapse, governing net sediment transport and short-term shoreline changes (Masselink and Puleo, 2006; Briganti et al., 2016).

Future work should prioritize addressing these limitations. A transition to a hybrid σ - z vertical coordinate system would offer a more robust representation of near-bed processes on sloping bathymetries, by leveraging the terrain-following continuity of σ -layers in shallow waters and the stability of z -levels in deeper regions. The incorporation of a cohesive sediment module, including flocculation dynamics, is essential for improving model fidelity in environments with significant mud and silt content. Finally, more extensive calibration and validation against high-resolution, long-term observational datasets are necessary to refine model parameterizations and constrain uncertainty.

Chapter 5

Concluding remarks

This thesis addressed a fundamental challenge in coastal-ocean modelling, which is the necessity of representing multiscale, strongly coupled physical interactions that govern the evolution of complex coastal systems. The traditional paradigm of isolated, single-process models, whether focusing exclusively on waves, circulation, or sediment dynamics, inherently neglects critical feedback mechanisms that modulate stress fields, water levels, and morphological response. This work departed from that fragmented approach by constructing an integrated numerical framework that progressively incorporates key physical couplings, from open-ocean to nearshore, and from surface to benthic processes.

5.1 Synthesis and research trajectory

The research was guided by three overarching objectives. First, to establish dynamically consistent two-way interactions between surface waves and currents, quantifying mutual exchange of momentum, energy, and sea state across the air-sea and water-column interfaces. Second, to bridge the gap between the hydrodynamic model and benthic layer by explicitly representing how marine vegetation transforms wave energy through biomechanical processes that respond to both environmental forcing and seasonal phenological cycles. Third, to integrate sediment transport and morphodynamic feedbacks within a unified framework, ensuring that evolving bathymetry dynamically influences the hydrodynamic response through mass conservation.

The framework was developed using two foundational models, SHYFEM-MPI, an unstructured-grid finite-element circulation solver, and WAVEWATCH III, a spectral wave model, both chosen for their demonstrated capability on complex domains, their active community support, and wide range of applications demonstrated in literature, from global to regional (Mentaschi et al. (2020), Causio et al. (2021), Causio et al. (2024)) and to coastal applications in different coupling configurations (Clementi et al. (2017); Pillai et al. (2022b)). The work demonstrates that such modular, progressively coupled architecture can simultaneously achieve physical rigor, computational scalability, and practical applicability to real-world coastal environments.

5.2 Framework advancement and physical insights

The coupled wave-circulation system revealed that traditional decoupled simulations substantially underestimate the complexity of storm-driven coastal hazards. During Medicane Ianos, wave-induced surge contributions reached 10–30% of the total water level, with pronounced spatial variability controlled by wave direction, local bathymetry, and the evolving wind field. More notably, the sea-state-dependent momentum flux through enhanced vertical mixing propagated thermal perturbations vertically to depths exceeding 100 m in coastal zones, demonstrating that wave-circulation coupling operates across the full water column, not merely at the surface. These magnitudes align with findings from previous coupled studies in other basins (Dietrich et al. (2011), Kim et al. (2010)), establishing that such couplings are not marginal effects but essential to hazard forecasting.

The incorporation of benthic vegetation into the spectral wave model introduced a novel dimension, moving from static structures to living canopies whose efficacy varies with phenological state. The development and validation of a flexible blade formulation, grounded in experimental studies (Luhar and Nepf (2011), Luhar and Nepf (2016)) from three substrate classes, demonstrated that accounting for biomechanical reconfiguration under wave forcing

reduces overestimation compared to rigid stem assumptions, with the average wave damping skill reaching up to 24%. More importantly, the work shows that seasonal leaf elongation and senescence patterns in *Posidonia oceanica* create monthly variations in wave dissipation of up to 10%, a temporal signature that single-valued parameterizations entirely miss. This finding reframes ecosystem wave impact, the phenological cycle becomes as important as vegetation flexibility itself, which can contribute up to half of the total attenuation. Such process-level insights, linking trait variability to functional ecosystem services, represent a conceptual advance beyond traditional static drag-based representations.

The sediment transport and morphodynamics framework successfully integrated enhanced bed stresses with waves and current-driven transport via a unified bedform roughness parameterization, intra-wave quasi-steady bedload transport, and two-way Exner-based feedbacks, coupling bed evolution to the free surface of the hydrodynamic system. Validation against established benchmarks, the wave-forced tidal inlet and the meandering river, demonstrated that the framework reproduces characteristic erosion-deposition patterns across diverse flow regimes. Critically, the inclusion of secondary flow corrections for curved channels where the morphodynamic evolution is fundamentally three-dimensional, accounts for the lateral redistribution of sediment that drives meander formation and channel migration. Application to the Tiber River delta, a complex system driven by river discharge, estuarine stratification, and storm-wave events, showed that the model captures the primary structure of hypopycnal plumes and reproduces spatial patterns of suspended sediment dispersal observable via satellite remote sensing. The agreement, albeit imperfect near the river mouth and at distal locations, validates the fundamental hydrodynamic-sediment transport coupling at the river-sea transition.

Collectively, these developments establish that an integrated modelling framework operating on a shared unstructured grid can simultaneously honor local bathymetric complexity, capture process interactions across multiple timescales (intra-wave oscillations, tidal cycles, seasonal

phenology, storm events), and produce quantitative predictions amenable to validation against diverse observational streams, such as in-situ and satellite imagery.

5.3 Limitations and pathways toward enhanced fidelity

Despite these advances, critical limitations remain, each pointing toward scientifically motivated future development. The present framework employs offline (one-way) wave forcing to the sediment module, deliberately chosen to constrain implementation complexity while establishing the hydrodynamic-morphodynamic core. However, this choice excludes a potentially significant feedback, as evolving bathymetry modulates wave propagation, shoaling, and breaking characteristics. In environments with rapid bed evolution, such as storm-driven scour near structures, or river mouth bar migration, changes in water depth alter local wave energy dissipation, which in turn influence the circulation-sediment feedback. Theoretical arguments and prior studies (Chapter 4) suggest this bathymetric-wave feedback can amplify morphological changes (Warner et al. (2008)). Full closure of this loop requires two-way wave-morphodynamics coupling, typically implemented through iterative exchange of updated bathymetry and wave spectra at coupling intervals, similar to the wave-circulation coupling strategy employed in Chapter 2. Parallel to this, the wave-vegetation module currently represents only the biomechanical influence of vegetation on wave dissipation. It does not feed back from wave-induced damage in terms of uprooting or blade fracture to dynamic vegetation state, nor does it couple to sediment dynamics to capture how vegetation trapping of suspended sediment builds matte structures and alters local bathymetry. Such sediment-vegetation feedbacks are documented in the literature (Gacia and Duarte (2001)) and operate on interannual timescales. Incorporating these requires hybrid frameworks combining benthic ecological growth models (e.g., incorporating light availability, nutrient uptake, grazing pressure) with sediment transport, a scientifically compelling direction.

The presented sediment framework treats all sediments as non-cohesive grains with prescribed settling velocities. This assumption holds for medium to coarse sands but breaks down for silts and clays, the dominant sediment classes in many river delta and estuarine systems. Fine sediments exhibit cohesive properties driven by electrostatic and polymeric forces, they can flocculate into aggregates with settling velocities by orders of magnitude faster than individual particles depending on shear and collision rates. The Tiber River application exposed this limitation, where the model systematically underestimated suspended sediment at distal plume locations, a discrepancy traceable to the exclusion of wash load, the finest silt and clay fractions that remain in suspension and travel far offshore as passive tracers.

The use of a terrain-following normalized (z^*) vertical coordinate system (Verri et al. (2023)), while computationally efficient, introduces a subtle but persistent limitation, the bottom-most layer exhibits discontinuous slope behaviour at sloping bathymetries, creating numerical artifacts in steep regions and during rapid bed evolution. This constraint was explicitly acknowledged in Section 4.2.1 and limits morphodynamic applications to scenarios with small bathymetric changes, non-intersecting water column layers, or depth-averaged model configurations. While adequate for the proof-of-concept applications presented here, this constraint becomes restrictive for long-term simulations (Mariotti and Murshid (2018)) or in environments with sustained net erosion or sedimentation, such as anthropogenic subsidence in deltas, coastal dikes, or inlet dynamics.

The proposed solution is a hybrid vertical coordinate system, merging sigma (σ) terrain-following layers in shallow waters with geopotential (z) levels in deeper regions, to eliminate the discontinuity in the bottom topography. Such hybrid systems have been extensively studied (Wang (2007)) and implemented in modern unstructured grid based models, such as SCHISM via SZ grid discretization (Zhang et al. (2016)). This development would extend applicability to long-term coastal evolution and support multi-decadal projections under climate forcing.

Another limitation comes from the use of the spectral wave models that represent waves via the action balance equation for phase-averaged spectral energy, averaging over the rapid oscillations of individual wave orbits. This phase-averaging inherently excludes the swash zone, the narrow strip where breaking waves run up the beach face and then drain back. Swash dynamics are highly unsteady, characterized by bore-like fronts, infiltration/exfiltration into porous sediment, and strong vertical accelerations (Briganti et al. (2016)); they violate the hydrostatic approximation central to shallow water and phase-averaged wave action. As a result, the morphological response within the swash zone, where sediment transport per unit area can exceed that of the nearshore region, is not represented. Swash-zone processes are sometimes approximated through empirical parameterizations of beach face rotation or through separate non-hydrostatic models (Zijlema et al. (2011)). Integration of such tools into the coastal framework would require a high-resolution grid refinement in shallow waters, a transition mechanism from phase-averaged wave forcing to phase-resolving or non-hydrostatic solvers, and a coupling of sediment transport between the two regimes.

5.4 Advancing toward predictive capability

The ultimate scientific goal of coastal-ocean modelling is not simulation for its own sake, but the development of high predictive capability for the coupled evolution of coastal morphology, ecosystem state, and human infrastructure under present climate and projected future conditions. Achieving this demands a paradigm shift toward integrated modelling that simultaneously resolve the fast dynamics of ocean circulation and waves, operating on hourly to daily timescales, alongside the slower adjustment of morphology and benthic habitats, unfolding over seasons to decades, all coupled within a unified computational framework. Such systems must explicitly represent biogeochemical feedbacks, including sediment carbon cycling, nutrient transformations, oxygen dynamics, and ecological responses such as vegetation growth and

habitat succession, which both influence and respond to physical forcing, while the systematic integration of diverse observational datasets constrains model parameters and enables rigorous assessment of predictive skill.

The modular system presented here provides a robust and extensible foundation for these advances. It serves as a transferable tool for coastal risk assessment and offers a tangible pathway toward the construction of the complex models for the coastal-ocean systems, thereby contributing directly to the scientific objectives of the UN Ocean Decade initiative.

Acknowledgements

I would like to express my sincere gratitude to my supervisors, Ivan Federico, for his unwavering support and guidance, Nadia Pinardi and Lorenzo Mentaschi, for their invaluable expertise and constructive advice, Salvatore Causio, for the engaging discussions and assistance with model implementations. Their knowledge and encouragement have profoundly shaped this work.

Special thanks are extended to Matthew D. Piggott for hosting me at Imperial College London and for providing exceptional mentorship, and to Stephan Kramer for the insightful discussions on numerical modelling and continuous support along the way. I was fortunate to interact closely with many members of the College, which made the research experience all the more enriching and memorable.

Finally, I would like to acknowledge my colleagues and friends at CMCC foundation and the University of Bologna, whose collaboration and vibrant camaraderie made this research not only productive but a genuinely enjoyable and memorable journey.

References

- Abdalla, S. and Bidlot, J.: Wind gustiness and air density effects and other key changes to wave model in CY25R1, Tech. Rep. Memorandum R60. 9/SA/0273, Research Department, ECMWF, Reading, U. K, 2002.
- Abdalla, S. and Cavaleri, L.: Effect of wind variability and variable air density on wave modeling, *Journal of Geophysical Research: Oceans*, 107, 17–1, 2002.
- Abdolali, A., Roland, A., Van Der Westhuysen, A., Meixner, J., Chawla, A., Hesser, T. J., Smith, J. M., and Sikiric, M. D.: Large-scale hurricane modeling using domain decomposition parallelization and implicit scheme implemented in WAVEWATCH III wave model, *Coastal Engineering*, 157, 103 656, 2020.
- Abdolali, A., Hesser, T. J., Anderson Bryant, M., Roland, A., Khalid, A., Smith, J., Ferreira, C., Mehra, A., and Sikiric, M. D.: Wave Attenuation by Vegetation: Model Implementation and Validation Study, *Frontiers in Built Environment*, 8, <https://doi.org/10.3389/fbuil.2022.891612>, 2022.
- Afentoulis, V., Papadimitriou, A., Belibassakis, K., and Tsoukala, V.: A coupled model for sediment transport dynamics and prediction of seabed morphology with application to 1DH /2DH coastal engineering problems, *Oceanologia*, 64, <https://doi.org/10.1016/j.oceano.2022.03.007>, 2022.
- Aijaz, S., Ghantous, M., Babanin, A. V., Ginis, I., Thomas, B., and Wake, G. W.: Nonbreaking wave-induced mixing in upper ocean during tropical cyclones using coupled hurricane-ocean-wave modeling, *Journal of Geophysical Research*, 122, 3939–3963, <https://doi.org/10.1002/2016JC012219>, 2017.
- Alari, V., Staneva, J., Breivik, Ø., Bidlot, J.-R., Mogensen, K., and Janssen, P.: Surface wave effects on water temperature in the Baltic Sea: simulations with the coupled NEMO-WAM model, *Ocean Dynamics*, 66, 917–930, 2016.
- Alcoverro, T., Duarte, C. M., and Romero, J.: Annual growth dynamics of *Posidonia oceanica*: contribution of large-scale versus local factors to seasonality, *Marine Ecology Progress Series*, 120, 203–210, <http://www.jstor.org/stable/24851876>, 1995.
- Alday, M., Accensi, M., Ardhuin, F., and Dodet, G.: A global wave parameter database for geophysical applications. Part 3: Improved forcing and spectral resolution, *Ocean Modelling*, 166, 101 848, <https://doi.org/10.1016/j.ocemod.2021.101848>, 2021.
- Alessandri, J., Pinardi, N., Federico, I., and Valentini, A.: Storm surge ensemble prediction system for Lagoons and transitional environments, *Weather and Forecasting*, 38, 1791–1806, 2023.
- Amoudry, L., Hsu, T.-J., and Liu, P.-F.: Two-phase model for sand transport in sheet flow regime, *Journal of Geophysical Research: Oceans*, 113, 2008.
- Amoudry, L. O. and Souza, A. J.: Deterministic coastal morphological and sediment transport modeling: A review and discussion, *Reviews of Geophysics*, 49, 2011.
- Anderson, M. E. and Smith, J.: Wave attenuation by flexible, idealized salt marsh vegetation, *Coastal Engineering*, 83, 82–92, 2014.

- Androulidakis, Y., Makris, C., Mallios, Z., Pytharoulis, I., Baltikas, V., and Krestenitis, Y.: Storm surges and coastal inundation during extreme events in the Mediterranean Sea: the IANOS Medicane, *Natural Hazards*, 117, 939–978, <https://doi.org/10.1007/s11069-023-05890-6>, 2023.
- Ardhuin, F., Rascle, N., and Belibassakis, K.: Explicit wave-averaged primitive equations using a generalized Lagrangian mean, *Ocean Modelling*, 20, 35–60, <https://doi.org/10.1016/j.ocemod.2007.07.001>, 2008.
- Ardhuin, F., Rogers, E., Babanin, A. V., Filipot, J.-F., Magne, R., Roland, A., van der Westhuysen, A., Queffelecoul, P., Lefèvre, J. M., Aouf, L., and Collard, F.: Semiempirical Dissipation Source Functions for Ocean Waves. Part I: Definition, Calibration, and Validation, *Journal of Physical Oceanography*, 40, 1917–1941, <https://doi.org/10.1175/2010JPO4324.1>, 2009.
- Ardhuin, F., Rogers, E., Babanin, A. V., Filipot, J.-F., Magne, R., Roland, A., Van Der Westhuysen, A., Queffelecoul, P., Lefevre, J.-M., Aouf, L., et al.: Semiempirical dissipation source functions for ocean waves. Part I: Definition, calibration, and validation, *Journal of Physical Oceanography*, 40, 1917–1941, 2010.
- Ardizzone, G., Belluscio, A., and Criscoli, A.: Atlante degli habitat dei fondali marini del Lazio. Regione Lazio., Direzione Regionale Capitale Naturale, Parchi e Aree Protette, ISBN 978-88-9377-088-0, 2018.
- Astraldi, M. and Gasparini, G.: The seasonal characteristics of the circulation in the Tyrrhenian Sea, Seasonal and interannual variability of the Western Mediterranean Sea, 46, 115–134, <https://doi.org/10.1029/CE046p0115>, 1994.
- Balaji, V., Maisonnave, E., Zadeh, N., Lawrence, B., Biercamp, J., Fladrich, U., Aloisio, G., Benson, R., Caubel, A., Durachta, J., Foujols, M.-A., Lister, G., Mocavero, S., Underwood, S., and Wright, G.: CPMIP: measurements of real computational performance of Earth system models in CMIP6, *Geoscientific Model Development*, 10, 19–34, <https://doi.org/10.5194/gmd-10-19-2017>, 2017.
- Barth, A., Beckers, J.-M., Troupin, C., Alvera-Azcárate, A., and Vandenbulcke, L.: Divand-1.0: n-dimensional variational data analysis for ocean observations, *Geoscientific Model Development*, 7, 225–241, 2014.
- Battjes, J. A. and Janssen, J. P. F. M.: Energy Loss and Set-Up Due to Breaking of Random Waves, pp. 569–587, American Society of Civil Engineers, <https://doi.org/10.1061/9780872621909.034>, 1978.
- Bauer, P., Thorpe, A., and Brunet, G.: The quiet revolution of numerical weather prediction, *Nature*, 525, 47–55, 2015.
- Benincasa, M., Falcini, F., Adduce, C., Sannino, G., and Santoleri, R.: Synergy of satellite remote sensing and numerical ocean modelling for coastal geomorphology diagnosis, *Remote Sensing*, 11, 2636, 2019.
- Bertin, X., Li, K., Roland, A., Zhang, Y. J., Breilh, J. F., and Chaumillon, E.: A modeling-based analysis of the flooding associated with Xynthia, central Bay of Biscay, *Coastal Engineering*, 94, 80–89, 2014.
- Bertin, X., Li, K., Roland, A., and Bidlot, J.-R.: The contribution of short-waves in storm surges: Two case studies in the Bay of Biscay, *Continental Shelf Research*, 96, 1–15, <https://doi.org/10.1016/j.csr.2015.01.005>, 2015.
- Beth Schaefer, R. and Nepf, H.: Wave damping by seagrass meadows in combined wave-current conditions, *Limnology and Oceanography*, 67, 1554–1565, <https://doi.org/10.1002/lno.12102>, 2022.
- Beudin, A., Kalra, T. S., Ganju, N. K., and Warner, J. C.: Development of a coupled wave-flow-vegetation interaction model, *Computers & Geosciences*, 100, 76–86, <https://doi.org/10.1016/j.cageo.2016.12.010>, 2017.

- Bidlot, J.-R. and Janssen, P.: Ocean-wave-related changes in the next model upgrade, <https://doi.org/10.21957/jb9py41a6f>, (data available at: <https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model>, last access: 17 June 2025), 2024.
- Blender Community: Blender - a 3D modelling and rendering package, v4.2 (2024-07-16), Blender Foundation, Blender Institute, Amsterdam, <http://www.blender.org>, 1994.
- Bonamano, S., de Mendoza, F. P., Piermattei, V., Martellucci, R., Madonia, A., Gnisci, V., Mancini, E., Fersini, G., Burgio, C., Marcelli, M., and Zappalà, G.: Mathematical models supporting the monitoring of Civitavecchia harbour (Rome), WIT Transactions on Modelling and Simulation, 59, 443–454, 2015.
- Bonamano, S., Piermattei, V., Madonia, A., Paladini de Mendoza, F., Pierattini, A., Martellucci, R., Stefanì, C., Zappalà, G., Caruso, G., and Marcelli, M.: The Civitavecchia Coastal Environment Monitoring System (C-CEMS): a new tool to analyze the conflicts between coastal pressures and sensitivity areas, Ocean Science, 12, 87–100, 2016.
- Bonamano, S., Piazzolla, D., Scanu, S., Mancini, E., Madonia, A., Piermattei, V., and Marcelli, M.: Modelling approach for the evaluation of burial and erosion processes on Posidonia oceanica meadows, Estuarine, Coastal and Shelf Science, 254, 107 321, <https://doi.org/10.1016/j.ecss.2021.107321>, 2021.
- Bonamano, S., Aurelio Peviani, M., Burgio, C. G., Fersini, G., and Marcelli, M.: High resolution numerical modeling supporting the evaluation of the WaveSAX-2 power generation in the coastal area around the Civitavecchia port, in: EGU General Assembly Conference Abstracts, EGU General Assembly Conference Abstracts, pp. EGU-7655, <https://doi.org/10.5194/egusphere-egu23-7655>, 2023.
- Bonamano, S., Federico, I., Causio, S., Piermattei, V., Piazzolla, D., Scanu, S., Madonia, A., Madonia, N., De Cillis, G., Jansen, E., Fersini, G., Coppini, G., and Marcelli, M.: River–coastal–ocean continuum modeling along the Lazio coast (Tyrrhenian Sea, Italy): Assessment of near river dynamics in the Tiber delta, Estuarine, Coastal and Shelf Science, 297, 108 618, <https://doi.org/10.1016/j.ecss.2024.108618>, 2024.
- Booij, N., Holthuijsen, L., and Ris, R.: The "SWAN" wave model for shallow water, in: Coastal engineering 1996, pp. 668–676, 1996.
- Borfecchia, F., Micheli, C., Cibic, T., Pignatelli, V., Cecco, L. D., Consalvi, N., Caroppo, C., Rubino, F., Poi, E. D., Kralj, M., and Negro, P. D.: Multispectral data by the new generation of high-resolution satellite sensors for mapping phytoplankton blooms in the Mar Piccolo of Taranto (Ionian Sea, southern Italy), European Journal of Remote Sensing, 52, 400 – 418, <https://doi.org/10.1080/22797254.2019.1625726>, 2019.
- Borum, J., Duarte, C., Krause-Jensen, D., and Greve, T.: European seagrasses: an introduction to monitoring and management., p. 88, Monitoring and Managing of European Seagrasses Project, ISBN 87-89143-21-3, <https://doi.org/doi.org/10.25607/OBP-1997>, 2004.
- Bosboom, J., Mol, M., Reniers, A., Stive, M., and De Valk, C.: Optimal sediment transport for morphodynamic model validation, Coastal Engineering, 158, 103 662, <https://doi.org/10.1016/j.coastaleng.2020.103662>, 2020.

- Bowen, A. J.: Rip currents: 1. Theoretical investigations, *Journal of Geophysical Research* (1896-1977), 74, 5467–5478, <https://doi.org/https://doi.org/10.1029/JC074i023p05467>, 1969.
- Bradley, K. and Houser, C.: Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments, *Journal of Geophysical Research: Earth Surface*, 114, <https://doi.org/10.1029/2007JF000951>, 2009.
- Breivik, Ø., Mogensen, K., Bidlot, J.-R., Balmaseda, M. A., and Janssen, P. A.: Surface wave effects in the NEMO ocean model: Forced and coupled experiments, *Journal of Geophysical Research: Oceans*, 120, 2973–2992, 2015.
- Briganti, R., Torres-Freyermuth, A., Baldock, T. E., Brocchini, M., Dodd, N., Hsu, T.-J., Jiang, Z., Kim, Y., Pintado-Patiño, J. C., and Postacchini, M.: Advances in numerical modelling of swash zone dynamics, *Coastal Engineering*, 115, 26–41, <https://doi.org/10.1016/j.coastaleng.2016.05.001>, 2016.
- Brus, S. R., Wolfram, P. J., Van Roekel, L. P., and Meixner, J. D.: Unstructured global to coastal wave modeling for the Energy Exascale Earth System Model using WAVEWATCH III version 6.07, *Geoscientific Model Development*, 14, 2917–2938, 2021.
- Bühler, O. and Jacobson, T. E.: Wave-driven currents and vortex dynamics on barred beaches, *Journal of Fluid Mechanics*, 449, 313–339, 2001.
- Buia, M. C., Gambi, M. C., and Dappiano, M.: Seagrass systems, *Biologia Marina Mediterranea*, 11, 133–183, 2004.
- Bulmer, R. H., Stewart-Sinclair, P. J., Lam-Gordillo, O., Mangan, S., Schwendenmann, L., and Lundquist, C. J.: Blue carbon habitats in Aotearoa New Zealand—opportunities for conservation, restoration, and carbon sequestration, *Restoration Ecology*, 32, <https://doi.org/10.1111/rec.14225>, 2024.
- Burchard, H. and Petersen, O.: Models of turbulence in the marine environment—a comparative study of two-equation turbulence models, *Journal of Marine Systems*, 21, 29–53, [https://doi.org/https://doi.org/10.1016/S0924-7963\(99\)00004-4](https://doi.org/https://doi.org/10.1016/S0924-7963(99)00004-4), 1999a.
- Burchard, H. and Petersen, O.: Models of turbulence in the marine environment—A comparative study of two-equation turbulence models, *Journal of Marine Systems*, 21, 29–53, 1999b.
- Camelo, J., Mayo, T. L., and Gutmann, E. D.: Projected climate change impacts on hurricane storm surge inundation in the coastal United States, *Frontiers in Built Environment*, 6, 588 049, <https://doi.org/10.3389/fbuil.2020.588049>, 2020.
- Causio, S., Ciliberti, S. A., Clementi, E., Coppini, G., and Lionello, P.: A modelling approach for the assessment of wave-currents interaction in the black sea, *Journal of Marine Science and Engineering*, 9, 893, <https://doi.org/10.3390/jmse9080893>, 2021.
- Causio, S., Federico, I., Jansen, E., Mentaschi, L., Ciliberti, S. A., Coppini, G., and Lionello, P.: The Black Sea near-past wave climate and its variability: a hindcast study, *Frontiers in Marine Science*, 11, 1406 855, <https://doi.org/10.3389/fmars.2024.1406855>, 2024.
- 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, *Ocean Science*, 21, 1105–1123, <https://doi.org/10.5194/os-21-1105-2025>, 2025.

- Cavaleri, L. and Rizzoli, P. M.: Wind wave prediction in shallow water: Theory and applications, *Journal of Geophysical Research: Oceans*, 86, 10 961–10 973, 1981.
- Cavicchia, L., von Storch, H., and Gualdi, S.: Mediterranean tropical-like cyclones in present and future climate, *Journal of Climate*, 27, 7493–7501, 2014.
- Charney, J. G., Fjörtoft, R., and Neumann, J. v.: Numerical integration of the barotropic vorticity equation, *Tellus*, 2, 237–254, <https://doi.org/10.3402/tellusa.v2i4.8607>, 1950.
- Chen, C., Liu, H., and Beardsley, R. C.: An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries, *Journal of atmospheric and oceanic technology*, 20, 159–186, [https://doi.org/10.1175/1520-0426\(2003\)020<0159:AUGFVT>2.0.CO;2](https://doi.org/10.1175/1520-0426(2003)020<0159:AUGFVT>2.0.CO;2), 2003.
- Chen, C., Beardsley, R., Cowles, G., Qi, J., Lai, Z., Gao, G., Stuebe, D., Xu, Q., Xue, P., Ge, J., et al.: An unstructured-grid, finite-volume community ocean model: FVCOM user manual, Sea Grant College Program, Massachusetts Institute of Technology Cambridge ..., 2012.
- Chen, Y., Li, Y., Thompson, C., Wang, X., Cai, T., and Chang, Y.: Differential sediment trapping abilities of mangrove and saltmarsh vegetation in a subtropical estuary, *Geomorphology*, 318, 270–282, 2018.
- Cid, A., Menéndez, M., Castanedo, S., Abascal, A. J., Méndez, F. J., and Medina, R.: Long-term changes in the frequency, intensity and duration of extreme storm surge events in southern Europe, *Climate Dynamics*, 46, 1503–1516, <https://doi.org/10.1007/s00382-015-2659-1>, 2016.
- Clare, M. C., Percival, J. R., Angeloudis, A., Cotter, C. J., and Piggott, M. D.: Hydro-morphodynamics 2D modelling using a discontinuous Galerkin discretisation, *Computers & Geosciences*, 146, 104 658, <https://doi.org/10.1016/j.cageo.2020.104658>, 2021.
- Clementi, E., Oddo, P., Drudi, M., Pinardi, N., Korres, G., and Grandi, A.: Coupling hydrodynamic and wave models: first step and sensitivity experiments in the Mediterranean Sea, *Ocean Dynamics*, 67, 1293–1312, 2017.
- Clementi, E., Korres, G., Cossarini, G., Ravdas, M., Federico, I., Goglio, A., Salon, S., Zacharioudaki, A., Pattanaro, M., and Coppini, G.: The September 2020 Medicane Ianos predicted by the Mediterranean forecasting systems. Copernicus ocean state report, 6, *J. Oper. Ocean.*, 15, s185–s192, 2022.
- Cobb, M. and Blain, C. A.: A coupled hydrodynamic-wave model for simulating wave and tidally-driven 2D circulation in inlets, in: *Estuarine and Coastal Modeling (2001)*, pp. 725–742, 2002.
- Consortium, E. B.: EMODnet Digital Bathymetry (DTM 2016), <http://doi.org/10.12770/c7b53704-999d-4721-b1a3-04ec60c87238>, 2016.
- Conti Neto, N., Lowe, R. J., Ghisalberti, M., Pomeroy, A., Reidenbach, M., Conde-Frias, M., and da Silva, R. F.: Spectral Wave Energy Dissipation by a Seagrass Meadow, *Journal of Geophysical Research: Oceans*, 130, e2024JC020 938, <https://doi.org/10.1029/2024JC020938>, e2024JC020938 2024JC020938, 2025.

- Couvelard, X., Lemarié, F., Samson, G., Redelsperger, J.-L., Ardhuin, F., Benshila, R., and Madec, G.: Development of a two-way-coupled ocean–wave model: assessment on a global NEMO (v3. 6)–WW3 (v6. 02) coupled configuration, *Geoscientific Model Development*, 13, 3067–3090, 2020.
- Cueto, J. E., Otero Díaz, L. J., Ospino-Ortiz, S. R., and Torres-Freyermuth, A.: The role of morphodynamics in predicting coastal flooding from storms on a dissipative beach with sea level rise conditions, *Natural Hazards and Earth System Sciences*, 22, 713–728, <https://doi.org/10.5194/nhess-22-713-2022>, 2022.
- D’Alpaos, A., Lanzoni, S., Marani, M., and Rinaldo, A.: Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics, *Journal of Geophysical Research: Earth Surface*, 112, <https://doi.org/10.1029/2006JF000537>, 2007.
- Dalrymple, R. A., Kirby, J. T., and Hwang, P. A.: Wave diffraction due to areas of energy dissipation, *Civil and Environmental Engineering*, 110, 67–79, <https://doi.org/https://ascelibrary.org/doi/10.1061/%28ASCE%290733-950X%281984%29110%3A1%2867%29>, 1984.
- Danilov, S.: Two finite-volume unstructured mesh models for large-scale ocean modeling, *Ocean Modelling*, 47, 14–25, <https://doi.org/10.1016/j.ocemod.2012.01.004>, 2012.
- Danilov, S.: Ocean modeling on unstructured meshes, *Ocean Modelling*, 69, 195–210, <https://doi.org/10.1016/j.ocemod.2013.05.005>, 2013.
- Di Maida, G., Tomasello, A., Sciandra, M., Pirrotta, M., Milazzo, M., and Calvo, S.: Effect of different substrata on rhizome growth, leaf biometry and shoot density of *Posidonia oceanica*, *Marine Environmental Research*, 87, 96–102, 2013.
- Diakakis, M., Mavroulis, S., Filis, C., Lozios, S., Vassilakis, E., Naoum, G., Soukis, K., Konsolaki, A., Kotsi, E., Theodorakatou, D., Skourtsos, E., Kranis, H., Gogou, M., Spyrou, N. I., Katsetsiadou, K.-N., and Lekkas, E.: Impacts of Medicanes on Geomorphology and Infrastructure in the Eastern Mediterranean, the Case of Medicane Ianos and the Ionian Islands in Western Greece, *Water*, 15, <https://www.mdpi.com/2073-4441/15/6/1026>, 2023.
- Dietrich, J., Zijlema, M., Westerink, J., Holthuijsen, L., Dawson, C., Luettich Jr, R., Jensen, R., Smith, J., Stelling, G., and Stone, G.: Modeling hurricane waves and storm surge using integrally-coupled, scalable computations, *Coastal Engineering*, 58, 45–65, 2011.
- Divinsky, B. V. and Kosyan, R. D.: Influence of the climatic variations in the wind waves parameters on the alongshore sediment transport, *Oceanologia*, 62, 190–199, 2020.
- Divinsky, B. V., Ryabchuk, D. V., Kosyan, R. D., and Sergeev, A. Y.: Development of the sandy coast: Hydrodynamic and morphodynamic conditions (on the example of the Eastern Gulf of Finland), *Oceanologia*, 63, 214–226, 2021.
- Donelan, M. A., Curcic, M., Chen, S. S., and Magnusson, A. K.: Modeling waves and wind stress, *Journal of Geophysical Research: Oceans*, 117, <https://doi.org/10.1029/2011JC007787>, 2012.
- Duarte, C. M.: Temporal biomass variability and production/biomass relationships of seagrass communities., *Marine ecology progress series*. Oldendorf, 51, 269–276, 1989.

- Dubi, A. and Tørum, A.: Wave damping by kelp vegetation, *Coastal Engineering Proceedings*, 1, 142–154, <https://doi.org/10.1061/9780784400890.012>, 1994.
- Dumas, E., Le Provost, C., and Poncet, A.: Feasibility of finite element methods for oceanic general circulation modelling, in: *Finite Elements in Water Resources: Proceedings of the 4th International Conference, Hannover, Germany, June 1982*, pp. 335–347, Springer, 1982.
- Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Agrawala, S., Bashmakov, I., Blanco, G., Broome, J., Bruckner, T., Brunner, S., Bustamante, M., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J.: Summary for policymakers. *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.
- Eldeberky, Y. and Battjes, J. A.: Spectral modeling of wave breaking: Application to Boussinesq equations, *Journal of Geophysical Research: Oceans*, 101, 1253–1264, <https://doi.org/10.1029/95JC03219>, 1996.
- Elkalay, K., Frangoulis, C., Skliris, N., Goffart, A., Gobert, S., Lepoint, G., and Hecq, J.-H.: A model of the seasonal dynamics of biomass and production of the seagrass *Posidonia oceanica* in the Bay of Calvi (Northwestern Mediterranean), *Ecological Modelling*, 167, 1–18, [https://doi.org/10.1016/S0304-3800\(03\)00074-7](https://doi.org/10.1016/S0304-3800(03)00074-7), 2003.
- Embury, O., Merchant, C. J., Good, S. A., Rayner, N. A., Høyer, J. L., Atkinson, C., Block, T., Alerskans, E., Pearson, K. J., Worsfold, M., et al.: Satellite-based time-series of sea-surface temperature since 1980 for climate applications, *Scientific Data*, 11, 326, 2024.
- EMODnet Bathymetry: EMODnet Digital Bathymetry (DTM 2020), <https://doi.org/10.12770/bb6a87dd-e579-4036-abe1-e649cea9881a>, [data set], 2020.
- Engelund, F.: Flow and bed topography in chanel bends, *J. Hyd. Div. ASCE*, 100, HY11, 1974.
- Entriiken, R. and Lordan, R.: Impacts of extreme events on transmission and distribution systems, in: *2012 IEEE Power and Energy Society General Meeting*, pp. 1–10, IEEE, 2012.
- Eric Jones, J. and Davies, A. M.: Application of a finite element model (TELEMAC) to computing the wind induced response of the Irish Sea, *Continental Shelf Research*, 26, 1519–1541, <https://doi.org/10.1016/j.csr.2006.03.013>, recent Developments in Physical Oceanographic Modelling: Part III, 2006.
- Escudier, R., Clementi, E., Omar, M., Cipollone, A., Pistoia, J., Aydogdu, A., Drudi, M., Grandi, A., Lyubartsev, V., Lecci, R., Cretí, S., Masina, S., Coppini, G., and Pinardi, N.: Mediterranean Sea Physical Reanalysis (CMEMS MED-Currents) (Version 1), Data set, https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1, 2020.
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geoscientific Model Development*, 9, 1937–1958, <https://doi.org/10.5194/gmd-9-1937-2016>, 2016.
- Federico, I., Pinardi, N., Coppini, G., Oddo, P., Lecci, R., and Mossa, M.: Coastal ocean forecasting with an unstructured grid model in the southern Adriatic and northern Ionian seas, *Natural Hazards and Earth System Sciences*, 17, 45–59, <https://doi.org/10.5194/nhess-17-45-2017>, 2017.

- Ferguson, R. and Church, M.: A simple universal equation for grain settling velocity, *Journal of sedimentary Research*, 74, 933–937, 2004.
- Ferrarin, C., Umgiesser, G., Cucco, A., Hsu, T.-W., Roland, A., and Amos, C. L.: Development and validation of a finite element morphological model for shallow water basins, *Coastal Engineering*, 55, 716–731, 2008.
- Ferrarin, C., Cucco, A., Umgiesser, G., Bellafore, D., and Amos, C. L.: Modelling fluxes of water and sediment between Venice Lagoon and the sea, *Continental Shelf Research*, 30, 904–914, <https://doi.org/10.1016/j.csr.2009.08.014>, 2010.
- Ferrarin, C., Roland, A., Bajo, M., Umgiesser, G., Cucco, A., Davolio, S., Buzzi, A., Malguzzi, P., and Drofa, O.: Tide-surge-wave modelling and forecasting in the Mediterranean Sea with focus on the Italian coast, *Ocean Modelling*, 61, 38–48, 2013.
- Ferrarin, C., Pantillon, F., Davolio, S., Bajo, M., Miglietta, M. M., Avolio, E., Carrió, D. S., Pytharoulis, I., Sanchez, C., Patlakas, P., et al.: Assessing the coastal hazard of Mediane Ianos through ensemble modelling, *Natural Hazards and Earth System Sciences*, 23, 2273–2287, 2023.
- Fix, G. J.: Finite Element Models for Ocean Circulation Problems, *SIAM Journal on Applied Mathematics*, 29, 371–387, <https://doi.org/10.1137/0129031>, 1975.
- Flaounas, E., Davolio, S., Raveh-Rubin, S., Pantillon, F., Miglietta, M., Gaertner, M., Hatzaki, M., Homar, V., Khodayar, S., Korres, G., et al.: Mediterranean cyclones: current knowledge and open questions on dynamics, prediction, climatology and impacts, *Weather Clim. Dynam.*, 3, 173–208, 2022.
- Folkard, A. M.: Hydrodynamics of model *Posidonia oceanica* patches in shallow water, *Limnology and Oceanography*, 50, 1592–1600, <https://doi.org/10.4319/lo.2005.50.5.1592>, 2005.
- Fonseca, M. S. and Cahalan, J. A.: A preliminary evaluation of wave attenuation by four species of seagrass, *Estuarine, Coastal and Shelf Science*, 35, 565–576, [https://doi.org/10.1016/S0272-7714\(05\)80039-3](https://doi.org/10.1016/S0272-7714(05)80039-3), 1992.
- Franz, G., Delpey, M. T., Brito, D., Pinto, L., Leitão, P., and Neves, R.: Modelling of sediment transport and morphological evolution under the combined action of waves and currents, *Ocean Science*, 13, 673–690, <https://doi.org/10.5194/os-13-673-2017>, 2017.
- Fredsoe, J. and Deigaard, R.: *Mechanics of coastal sediment transport*, vol. 3, World scientific publishing company, 1992.
- Gacia, E. and Duarte, C. M.: Sediment retention by a Mediterranean *Posidonia oceanica* meadow: the balance between deposition and resuspension, *Estuarine, coastal and shelf science*, 52, 505–514, 2001.
- Galappatti, G. and Vreugdenhil, C.: A depth-integrated model for suspended sediment transport, *Journal of Hydraulic Research*, 23, 359–377, <https://doi.org/10.1080/00221688509499345>, 1985.
- Gerritsen, H., De Goede, E., Platzek, F., Genseberger, M., van Kester, J., and Uittenbogaard, R.: Validation document Delft3D-FLOW-A software system for 3D simulations, 2007.
- Geuzaine, C. and Remacle, J.-F.: Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities, *International Journal for Numerical Methods in Engineering*, 79, 1309–1331, <https://doi.org/10.1002/nme.2579>, 2009.

- Giovannetti, E., Lasagna, R., Montefalcone, M., Bianchi, C. N., Albertelli, G., and Morri, C.: Inconsistent responses to substratum nature in *Posidonia oceanica* meadows: An integration through complexity levels?, *Chemistry and Ecology*, 24, 83–91, <https://doi.org/10.1080/02757540801966439>, 2008.
- Giraud, G.: Recensement des floraisons de *Posidonia oceanica* (Linne) Delile en Mediterranee., *Rapports et Proces-Verbaux des Reunions-Commission Internationale pour l'Exploration Scientifique de la Mer Mediterranee (CIESM)*. v. 24 (4)., 1977.
- Giraud, G., Boudouresque, C.-F., Cinelli, F., Fresi, E., and Mazzella, L.: Observations sur l'herbier de *Posidonia oceanica* (L.) Delile autour de l'Ile d'Ischia (Italie), *Giornale botanico italiano*, 113, 261–274, <https://doi.org/10.1080/11263507909426647>, 1979.
- Gnisci, V., de Martiis, S. C., Belmonte, A., Micheli, C., Piermattei, V., Bonamano, S., and Marcelli, M.: Assessment of the ecological structure of *Posidonia oceanica* (L.) Delile on the northern coast of Lazio, Italy (central Tyrrhenian, Mediterranean), *Italian Botanist*, 9, 1–19, 2020.
- Graf, W. L.: The impact of suburbanization on fluvial geomorphology, *Water Resources Research*, 11, 690–692, 1975.
- Grant, W. D. and Madsen, O. S.: Combined wave and current interaction with a rough bottom, *Journal of Geophysical Research: Oceans*, 84, 1797–1808, 1979.
- Grant, W. D. and Madsen, O. S.: The continental-shelf bottom boundary layer, *Annual review of fluid mechanics*, 18, 265–305, 1986.
- Gupta, A., Behera, M. R., and Heidarpour, A.: Numerical Modeling of Wave Damping Induced by Emerged Moving Vegetation, in: *International Conference on Offshore Mechanics and Arctic Engineering*, vol. 84379, p. V06AT06A013, American Society of Mechanical Engineers, <https://doi.org/10.1115/OMAE2020-18588>, 2020.
- Haklay, M. and Weber, P.: Openstreetmap: User-generated street maps, *IEEE Pervasive computing*, 7, 12–18, <https://doi.org/10.1109/MPRV.2008.80>, 2008.
- Hashemi, M. R. and Neill, S. P.: The role of tides in shelf-scale simulations of the wave energy resource, *Renewable Energy*, 69, 300–310, <https://doi.org/10.1016/j.renene.2014.03.052>, 2014.
- Hasselmann, K., Barnett, T. P., Bouws, E., Carlson, H., Cartwright, D. E., Enke, K., Ewing, J. A., Gienapp, A., Hasselmann, D. E., Kruseman, P., Meerburg, A., Müller, P., Olbers, D. J., Richter, K., Shell, W., and Walden, H.: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)., *Ergaenzungsheft zur Deutschen Hydrographischen Zeitschrift, Reihe A*, pp. 1–95, 1973.
- Hasselmann, S. and Hasselmann, K. F.: Computations and Parameterizations of the Nonlinear Energy Transfer in a Gravity-Wave Spectrum. Part I: A New Method for Efficient Computations of the Exact Nonlinear Transfer Integral, *Journal of Physical Oceanography*, 15, 1369–1377, [https://doi.org/10.1175/1520-0485\(1985\)015<1369:CAPOTN>2.0.CO;2](https://doi.org/10.1175/1520-0485(1985)015<1369:CAPOTN>2.0.CO;2), 1985.
- Hasselmann, S., Hasselmann, K., Allender, J., and Barnett, T.: Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum. Part II: Parameterizations of the nonlinear energy transfer for application in wave models, *Journal of Physical Oceanography*, 15, 1378–1391, 1985.

- Hellerman, S. and Rosenstein, M.: Normal monthly wind stress over the world ocean with error estimates, *Journal of Physical Oceanography*, 13, 1093–1104, 1983.
- Hemminga, M. A. and Duarte, C. M.: *Seagrass ecology*, Cambridge University Press, ISBN 0521661846, 2000.
- Hervouet, J.-M.: *Hydrodynamics of free surface flows: modelling with the finite element method*, John Wiley & Sons, 2007.
- Hinkel, J., Nicholls, R. J., Tol, R. S., Wang, Z. B., Hamilton, J. M., Boot, G., Vafeidis, A. T., McFadden, L., Ganopolski, A., and Klein, R. J.: A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA, *Global and Planetary change*, 111, 150–158, 2013.
- Hoagland, S. W., Jeffries, C. R., Irish, J. L., Weiss, R., Mandli, K., Vitousek, S., Johnson, C. M., and Cialone, M. A.: Advances in Morphodynamic Modeling of Coastal Barriers: A Review, *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 149, 03123 001, <https://doi.org/10.1061/JWPED5.WWENG-1825>, 2023.
- Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., Foden, P. R., Gordon, K. M., Jevrejeva, S., and Pugh, J.: New data systems and products at the permanent service for mean sea level, *Journal of Coastal Research*, 29, 493–504, 2013.
- Hsiao, S.-C., Chen, H., Chen, W.-B., Chang, C.-H., and Lin, L.-Y.: Quantifying the contribution of nonlinear interactions to storm tide simulations during a super typhoon event, *Ocean Engineering*, 194, 106 661, 2019.
- Iacono, R., Napolitano, E., Palma, M., and Sannino, G.: The Tyrrhenian sea circulation: A review of recent work, *Sustainability*, 13, 6371, <https://doi.org/10.3390/su13116371>, 2021.
- Iadanza, C. and Napolitano, F.: Sediment transport time series in the Tiber River, *Physics and Chemistry of the Earth, Parts A/B/C*, 31, 1212–1227, 2006.
- Infantes, E., Orfila, A., Simarro, G., Terrados, J., Luhar, M., and Nepf, H.: Effect of a seagrass (*Posidonia oceanica*) meadow on wave propagation, *Marine Ecology Progress Series*, 456, 63–72, <https://doi.org/10.3354/meps09754>, 2012.
- Jacob, B., Dolch, T., Wurpts, A., and Staneva, J.: Evaluation of seagrass as a nature-based solution for coastal protection in the German Wadden Sea, *Ocean Dynamics*, 73, 699–727, <https://doi.org/10.1007/s10236-023-01577-5>, 2023.
- Janssen, P. A.: Wave-induced stress and the drag of air flow over sea waves, *Journal of Physical Oceanography*, 19, 745–754, 1989.
- Janssen, P. A.: Quasi-linear theory of wind-wave generation applied to wave forecasting, *Journal of physical oceanography*, 21, 1631–1642, 1991.
- Jeong, J.-S. and Lee, H. S.: Unstructured Grid-Based River–Coastal Ocean Circulation Modeling towards a Digital Twin of the Seto Inland Sea, *Applied Sciences*, 13, <https://doi.org/10.3390/app13148143>, 2023.
- Jo, J., Kim, S., Mori, N., and Mase, H.: Combined storm surge and wave overtopping inundation based on fully coupled storm surge-wave-tide model, *Coastal Engineering*, 189, 104 448, 2024.
- Johannessen, S. C.: How to quantify blue carbon sequestration rates in seagrass meadow sediment: geochemical method and troubleshooting, *Carbon Footprints*, <https://doi.org/10.20517/cf.2023.37>, 2023.
- Julien, P. Y.: *Erosion and sedimentation*, Cambridge university press, 2010.

- Jung, B. M., Fernandes, E. H., Möller Jr, O. O., and García-Rodríguez, F.: Estimating suspended sediment concentrations from river discharge data for reconstructing gaps of information of long-term variability studies, *Water*, 12, 2382, 2020.
- Kapolnai, A., Werner, F. E., and Blanton, J. O.: Circulation, mixing, and exchange processes in the vicinity of tidal inlets: A numerical study, *Journal of Geophysical Research: Oceans*, 101, 14 253–14 268, 1996.
- Kara, A. B., Wallcraft, A. J., Hurlburt, H. E., and Stanev, E.: Air–sea fluxes and river discharges in the Black Sea with a focus on the Danube and Bosphorus, *Journal of Marine Systems*, 74, 74–95, 2008.
- Kärnä, T., Kramer, S. C., Mitchell, L., Ham, D. A., Piggott, M. D., and Baptista, A. M.: Thetis coastal ocean model: discontinuous Galerkin discretization for the three-dimensional hydrostatic equations, *Geoscientific Model Development*, 11, 4359–4382, <https://doi.org/10.5194/gmd-11-4359-2018>, 2018.
- Kim, S. Y., Yasuda, T., and Mase, H.: Numerical analysis of effects of tidal variations on storm surges and waves, *Applied Ocean Research*, 30, 311–322, 2008.
- Kim, S. Y., Yasuda, T., and Mase, H.: Wave set-up in the storm surge along open coasts during Typhoon Anita, *Coastal Engineering*, 57, 631–642, 2010.
- Koch, F. and Flokstra, C.: Bed level computations for curved alluvial channels, 240, Delft Hydraulics Laboratory, 1980.
- Koftis, T., Prinos, P., and Stratigaki, V.: Wave damping over artificial *Posidonia oceanica* meadow: A large-scale experimental study, *Coastal Engineering*, 73, 71–83, <https://doi.org/10.1016/j.coastaleng.2012.10.007>, 2013.
- Komen, G., Hasselmann, S., and Hasselmann, K.: On the existence of a fully developed wind-sea spectrum, *Journal of physical oceanography*, 14, 1271–1285, 1984.
- Korres, G., Oikonomou, C., Denaxa, D., and Sotiropoulou, M.: Mediterranean Sea Waves Analysis and Forecast (Copernicus Marine Service MED-Waves, MEDWAM4 system) (Version 1) [Data set]., 2023a.
- Korres, G., Oikonomou, C., Denaxa, D., and Sotiropoulou, M.: Mediterranean Sea Waves Monthly Climatology (CMS Med-Waves, MedWAM3 system) (Version 1), https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_WAV_006_012_CLIM, [data set], 2023b.
- Lanzoni, S. and Seminara, G.: Long-term evolution and morphodynamic equilibrium of tidal channels, *Journal of Geophysical Research: Oceans*, 107, 1–1–1–13, <https://doi.org/10.1029/2000JC000468>, 2002.
- Large, W. B.: Surface fluxes for practitioners of global ocean data assimilation, in: *Ocean weather forecasting: An integrated view of oceanography*, pp. 229–270, Springer, 2006.
- Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., Barrett, K., et al.: Climate change 2023: Synthesis Report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change, <https://doi.org/10.59327/IPCC/AR6-9789291691647>, 2023.
- Lei, J. and Nepf, H.: Wave damping by flexible vegetation: Connecting individual blade dynamics to the meadow scale, *Coastal Engineering*, 147, 138–148, <https://doi.org/10.1016/j.coastaleng.2019.01.008>, 2019.
- Lesser, G., Roelvink, J., Van Kester, J., and Stelling, G.: Development and validation of a three-dimensional morphological model, *Coastal Engineering*, 51, 883–915, <https://doi.org/10.1016/j.coastaleng.2004.07.014>, 2004.

- Li, M. Z. and Amos, C. L.: SEDTRANS96: the upgraded and better calibrated sediment-transport model for continental shelves, *Computers & Geosciences*, 27, 619–645, [https://doi.org/10.1016/S0098-3004\(00\)00120-5](https://doi.org/10.1016/S0098-3004(00)00120-5), 2001.
- Li, Y., Peng, S., Wang, J., and Yan, J.: Impacts of nonbreaking wave-stirring-induced mixing on the upper ocean thermal structure and typhoon intensity in the South China Sea, *Journal of Geophysical Research: Oceans*, 119, 5052–5070, <https://doi.org/10.1002/2014/JC009956>, 2014.
- Longuet-Higgins, M. and Stewart, R.: Radiation stresses in water waves; a physical discussion, with applications, *Deep Sea Research and Oceanographic Abstracts*, 11, 529–562, [https://doi.org/10.1016/0011-7471\(64\)90001-4](https://doi.org/10.1016/0011-7471(64)90001-4), 1964.
- Longuet-Higgins, M. S.: Longshore currents generated by obliquely incident sea waves: 1, *Journal of geophysical research*, 75, 6778–6789, 1970.
- Longuet-Higgins, M. S. and Stewart, R.: The changes in amplitude of short gravity waves on steady non-uniform currents, *Journal of fluid mechanics*, 10, 529–549, 1961.
- Longuet-Higgins, M. S. and Stewart, R.: Radiation stress and mass transport in gravity waves, with application to ‘surf beats’, *Journal of Fluid Mechanics*, 13, 481–504, 1962.
- Luhar, M. and Nepf, H.: Wave-induced dynamics of flexible blades, *Journal of Fluids and Structures*, 61, 20–41, <https://doi.org/10.1016/j.jfluidstructs.2015.11.007>, 2016.
- Luhar, M. and Nepf, H. M.: Flow-induced reconfiguration of buoyant and flexible aquatic vegetation, *Limnology and Oceanography*, 56, 2003–2017, <https://doi.org/10.4319/lo.2011.56.6.2003>, 2011.
- Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., and Aarninkhof, S.: The state of the world’s beaches, *Scientific reports*, 8, 6641, 2018.
- Løvås, S. M. and Tørum, A.: Effect of the kelp *Laminaria hyperborea* upon sand dune erosion and water particle velocities, *Coastal Engineering*, 44, 37–63, [https://doi.org/10.1016/S0378-3839\(01\)00021-7](https://doi.org/10.1016/S0378-3839(01)00021-7), 2001.
- Madsen, J. D., Chambers, P. A., James, W. F., Koch, E. W., and Westlake, D. F.: The interaction between water movement, sediment dynamics and submersed macrophytes, *Hydrobiologia*, 444, 71–84, <https://doi.org/10.1023/A:1017520800568>, 2001.
- Manca, E., Cáceres, I., Alsina, J., Stratigaki, V., Townend, I., and Amos, C.: Wave energy and wave-induced flow reduction by full-scale model *Posidonia oceanica* seagrass, *Continental Shelf Research*, 50–51, 100–116, <https://doi.org/10.1016/j.csr.2012.10.008>, 2012.
- Marbà, N., Díaz-Almela, E., and Duarte, C. M.: Mediterranean seagrass (*Posidonia oceanica*) loss between 1842 and 2009, *Biological Conservation*, 176, 183–190, <https://doi.org/10.1016/j.biocon.2014.05.024>, 2014.
- Marcelli, M., Piermattei, V., Bonamano, S., Causio, S., Ceccherelli, G., Coppini, G., De Lucia, G. A., Del Negro, P., Falace, A., Federico, I., Madonia, A., Mentaschi, L., Piazzolla, D., Pinardi, N., Sarà, G., Savini, A., Scanu, S., and Fersini, G.: RENOVATE Project: ecosystem approach for compensation and mitigation actions in the coastal marine environment, in: *EGU General Assembly Conference Abstracts*, pp. EGU–13 554, <https://doi.org/10.5194/egusphere-egu23-13554>, 2023.

- Mariotti, G. and Murshid, S.: A 2D Tide-Averaged Model for the Long-Term Evolution of an Idealized Tidal Basin-Inlet-Delta System, *Journal of Marine Science and Engineering*, 6, <https://doi.org/10.3390/jmse6040154>, 2018.
- Masselink, G. and Puleo, J. A.: Swash-zone morphodynamics, *Continental Shelf Research*, 26, 661–680, <https://doi.org/10.1016/j.csr.2006.01.015>, 2006.
- McCall, R., Masselink, G., Poate, T., Roelvink, J., and Almeida, L.: Modelling the morphodynamics of gravel beaches during storms with XBeach-G, *Coastal Engineering*, 103, 52–66, 2015.
- McWilliams, J. C., Restrepo, J. M., and Lane, E. M.: An asymptotic theory for the interaction of waves and currents in coastal waters, *Journal of Fluid Mechanics*, 511, 135–178, <https://doi.org/10.1017/S0022112004009358>, 2004.
- Mellor, G.: The three-dimensional current and surface wave equations, *Journal of physical oceanography*, 33, 1978–1989, 2003.
- Mendez, F. J. and Losada, I. J.: An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields, *Coastal Engineering*, 51, 103–118, <https://doi.org/10.1016/j.coastaleng.2003.11.003>, 2004.
- Mentaschi, L., Vousdoukas, M., Montblanc, T. F., Kakoulaki, G., Voukouvalas, E., Besio, G., and Salamon, P.: Assessment of global wave models on regular and unstructured grids using the Unresolved Obstacles Source Term, *Ocean Dynamics*, 70, 1475–1483, 2020.
- Mentaschi, L., Vousdoukas, M. I., García-Sánchez, G., Fernández-Montblanc, T., Roland, A., Voukouvalas, E., Federico, I., Abdolali, A., Zhang, Y. J., and Feyen, L.: A global unstructured, coupled, high-resolution hindcast of waves and storm surge, *Frontiers in Marine Science*, 10, 1233 679, 2023.
- Meucci, A., Young, I. R., Hemer, M., Kirezci, E., and Ranasinghe, R.: Projected 21st century changes in extreme wind-wave events, *Science advances*, 6, eaaz7295, <https://doi.org/10.1126/sciadv.aaz7295>, 2020.
- Micaletto, G., Barletta, I., Mocavero, S., Federico, I., Epicoco, I., Verri, G., Coppini, G., Schiano, P., Aloisio, G., and Pinardi, N.: Parallel implementation of the SHYFEM (System of Hydrodynamic Finite Element Modules) model, *Geoscientific Model Development*, 15, 6025–6046, <https://doi.org/10.5194/gmd-15-6025-2022>, 2022.
- Miche, A.: Mouvements ondulatoire de la mer en profondeur croissante ou décroissante. Forme limite de la houle lors de son déferlement. Application aux digues maritimes. Deuxième partie. Mouvements ondulatoires périodiques en profondeur régulièrement décroissante, *Ann., Ponts Chaussées*, 114, 25–78, 131–164, 270–292, 369–406, 1944.
- Miles, J. W.: On the generation of surface waves by shear flows, *Journal of Fluid Mechanics*, 3, 185–204, 1957.
- Molenaar, H., Barthélémy, D., de Reffye, P., Meinesz, A., and Mialet, I.: Modelling architecture and growth patterns of *Posidonia oceanica*, *Aquatic Botany*, 66, 85–99, [https://doi.org/10.1016/S0304-3770\(99\)00071-6](https://doi.org/10.1016/S0304-3770(99)00071-6), 2000.
- Monismith, S. G., Hirsh, H., Batista, N., Francis, H., Egan, G., and Dunbar, R. B.: Flow and Drag in a Seagrass Bed, *Journal of Geophysical Research: Oceans*, 124, 2153–2163, <https://doi.org/10.1029/2018JC014862>, 2019.
- Morim, J., Hemer, M., Wang, X. L., Cartwright, N., Trenham, C., Semedo, A., Young, I., Brichenno, L., Camus, P., Casas-Prat, M., et al.: Robustness and uncertainties in global multivariate wind-wave climate projections, *Nature Climate Change*, 9, 711–718, 2019.

- Morim, J., Vitousek, S., Hemer, M., Reguero, B., Erikson, L., Casas-Prat, M., Wang, X. L., Semedo, A., Mori, N., Shimura, T., et al.: Global-scale changes to extreme ocean wave events due to anthropogenic warming, *Environmental Research Letters*, 16, 074056, 2021.
- Moulinec, C., Denis, C., Pham, C.-T., Rougé, D., Hervouet, J.-M., Razafindrakoto, E., Barber, R., Emerson, D., and Gu, X.-J.: TELEMAC: An efficient hydrodynamics suite for massively parallel architectures, *Computers & Fluids*, 51, 30–34, <https://doi.org/10.1016/j.compfluid.2011.07.003>, 2011.
- Myrhaug, D.: Bottom friction beneath random waves, *Coastal Engineering*, 24, 259–273, 1995.
- Neumeier, U., Ferrarin, C., Amos, C. L., Umgiesser, G., and Li, M. Z.: Sedtrans05: An improved sediment-transport model for continental shelves and coastal waters with a new algorithm for cohesive sediments, *Computers & Geosciences*, 34, 1223–1242, <https://doi.org/10.1016/j.cageo.2008.02.007>, 2008.
- Nielsen, P.: Coastal bottom boundary layers and sediment transport, vol. 4, World scientific, 1992.
- Noori, A., Mohajeri, S. H., Delnavaz, M., and Rezazadeh, R.: A spatiotemporal monitoring model of TSM and TDS in arid region lakes utilizing Sentinel-2 imagery, *Journal of Arid Environments*, 216, 105024, 2023.
- Nowacki, D. J., Beudin, A., and Ganju, N. K.: Spectral wave dissipation by submerged aquatic vegetation in a back-barrier estuary, *Limnology and Oceanography*, 62, 736–753, <https://doi.org/10.1002/lno.10456>, 2017.
- Oprandi, A., Mucerino, L., De Leo, F., Bianchi, C., Morri, C., Azzola, A., Benelli, F., Besio, G., Ferrari, M., and Montefalcone, M.: Effects of a severe storm on seagrass meadows, *Science of the Total Environment*, 748, 141373, <https://doi.org/10.1016/j.scitotenv.2020.141373>, 2020a.
- Oprandi, A., Mucerino, L., De Leo, F., Bianchi, C. N., Morri, C., Azzola, A., Benelli, F., Besio, G., Ferrari, M., and Montefalcone, M.: Effects of a severe storm on seagrass meadows, *Science of The Total Environment*, 748, <https://doi.org/10.1016/j.scitotenv.2020.141373>, 2020b.
- Ott, J. A.: Growth and Production in *Posidonia Oceanica* (L.) Delile, *Marine Ecology*, 1, 47–64, <https://doi.org/10.1111/j.1439-0485.1980.tb00221.x>, 1980.
- Owens, R. and Hewson, T.: ECMWF Forecast User Guide, Tech. rep., ECMWF, Reading, <https://doi.org/10.21957/m1cs7h>, 2018.
- Paola, C. and Voller, V. R.: A generalized Exner equation for sediment mass balance, *Journal of Geophysical Research: Earth Surface*, 110, 2005.
- Park, K., Federico, I., Di Lorenzo, E., Ezer, T., Cobb, K. M., Pinardi, N., and Coppini, G.: The contribution of hurricane remote ocean forcing to storm surge along the Southeastern US coast, *Coastal Engineering*, 173, 104098, 2022.
- Paul, M., Bouma, T., and Amos, C.: Wave attenuation by submerged vegetation: combining the effect of organism traits and tidal current, *Marine Ecology Progress Series*, 444, 31–41, <https://doi.org/10.3354/meps09489>, 2012.
- Paynter, S.: Nature-based solutions: estuarine restoration for water quality, seagrass and ecological improvement, *Proceedings of the Institution of Civil Engineers - Civil Engineering*, <https://doi.org/10.1680/jcien.24.00917>, 2024.

- Pergent-Martini, C., Pergent, G., Monnier, B., Boudouresque, C.-F., Mori, C., and Valette-Sansevin, A.: Contribution of Posidonia oceanica meadows in the context of climate change mitigation in the Mediterranean Sea, *Marine Environmental Research*, 165, 105–236, <https://doi.org/10.1016/j.marenvres.2020.105236>, 2021.
- Phillips, N. A.: The general circulation of the atmosphere: A numerical experiment, *Quarterly Journal of the Royal Meteorological Society*, 82, 123–164, 1956.
- Piazzolla, D., Scanu, S., Mancuso, F. P., Bosch-Belmar, M., Bonamano, S., Madonia, A., Scagnoli, E., Tantillo, M. F., Russi, M., Savini, A., Fersini, G., Sarà, G., Coppini, G., Marcelli, M., and Piermattei, V.: An integrated approach for the benthic habitat mapping based on innovative surveying technologies and ecosystem functioning measurements, *Scientific Reports*, 14, 5888, <https://doi.org/10.1038/s41598-024-56662-6>, 2024.
- Piggott, M. D., Gorman, G. J., Pain, C. C., Allison, P. A., Candy, A. S., Martin, B. T., and Wells, M. R.: A new computational framework for multi-scale ocean modelling based on adapting unstructured meshes, *International Journal for Numerical Methods in Fluids*, 56, 1003–1015, <https://doi.org/10.1002/flid.1663>, 2008.
- Pillai, U., Pinardi, N., Federico, I., Causio, S., Trotta, F., Unguendoli, S., Valentini, A., et al.: Wind-wave characteristics and extremes along the Emilia-Romagna coast, *Natural Hazards and Earth System Sciences*, 22, 3413–3433, 2022a.
- Pillai, U. P. A., Pinardi, N., Alessandri, J., Federico, I., Causio, S., Unguendoli, S., Valentini, A., and Staneva, J.: A Digital Twin modelling framework for the assessment of seagrass Nature Based Solutions against storm surges, *Science of the Total Environment*, 847, <https://doi.org/10.1016/j.scitotenv.2022.157603>, 2022b.
- Pinardi, N., Bonaduce, A., Navarra, A., Dobricic, S., and Oddo, P.: The Mean Sea Level Equation and Its Application to the Mediterranean Sea, *Journal of Climate*, 27, 442–447, <https://doi.org/10.1175/JCLI-D-13-00139.1>, 2014.
- Pisano, A., Nardelli, B. B., Tronconi, C., and Santoleri, R.: The new Mediterranean optimally interpolated pathfinder AVHRR SST Dataset (1982–2012), *Remote Sensing of Environment*, 176, 107–116, 2016.
- Pitarch, J., Falcini, F., Nardin, W., Brando, V., Di Cicco, A., and Marullo, S.: Linking flow-stream variability to grain size distribution of suspended sediment from a satellite-based analysis of the Tiber River plume (Tyrrhenian Sea), *Scientific reports*, 9, 19 729, 2019.
- Platzman, G. W.: The ENIAC computations of 1950—Gateway to numerical weather prediction, *Bulletin of the American Meteorological Society*, 60, 302–312, 1979.
- Price, J. F.: Upper ocean response to a hurricane, *Journal of Physical Oceanography*, 11, 153–175, 1981.
- Pye, K. and Blott, S. J.: Coastal processes and morphological change in the Dunwich-Sizewell area, Suffolk, UK, *Journal of Coastal Research*, 22, 453–473, 2006.
- Rathgeber, F., Ham, D. A., Mitchell, L., Lange, M., Luporini, F., McRae, A. T., Bercea, G.-T., Markall, G. R., and Kelly, P. H.: Firedrake: automating the finite element method by composing abstractions, *ACM Transactions on Mathematical Software (TOMS)*, 43, 1–27, <https://doi.org/10.1145/2998441>, 2016.
- Reidenbach, M. A., Monismith, S. G., Koseff, J. R., Yahel, G., and Genin, A.: Boundary layer turbulence and flow structure over a fringing coral reef, *Limnology and Oceanography*, 51, 1956–1968, <https://doi.org/10.4319/lo.2006.51.5.1956>, 2006.

- Remacle, J.-F., Henrotte, F., Carrier-Baudouin, T., Béchet, E., Marchandise, E., Geuzaine, C., and Mouton, T.: A frontal Delaunay quad mesh generator using the L_∞ norm, *International Journal for Numerical Methods in Engineering*, 94, 494–512, <https://doi.org/10.1002/nme.4458>, 2013.
- Ricchiuto, M., Csík, Á., and Deconinck, H.: Residual distribution for general time-dependent conservation laws, *Journal of Computational Physics*, 209, 249–289, <https://doi.org/10.1016/J.JCP.2005.03.003>, 2005.
- Richardson, L. F.: *Weather prediction by numerical process*, Franklin Classics, 1922.
- Roca, G., Alcoverro, T., de Torres, M., Manzanera, M., Martínez-Crego, B., Bennett, S., Farina, S., Pérez, M., and Romero, J.: Detecting water quality improvement along the Catalan coast (Spain) using stress-specific biochemical seagrass indicators, *Ecological Indicators*, 54, 161–170, <https://doi.org/10.1016/j.ecolind.2015.02.031>, 2015.
- Roelvink, D. and Costas, S.: Coupling nearshore and aeolian processes: XBeach and duna process-based models, *Environmental Modelling & Software*, 115, 98–112, 2019.
- Roelvink, D., Reniers, A., Van Dongeren, A., De Vries, J. V. T., McCall, R., and Lescinski, J.: Modelling storm impacts on beaches, dunes and barrier islands, *Coastal engineering*, 56, 1133–1152, 2009.
- Roland, A., Cucco, A., Ferrarin, C., Hsu, T.-W., Liao, J.-M., Ou, S.-H., Umgiesser, G., and Zanke, U.: On the development and verification of a 2-D coupled wave-current model on unstructured meshes, *Journal of Marine Systems*, 78, S244–S254, 2009.
- Romero, R. and Emanuel, K.: Medican risk in a changing climate, *Journal of Geophysical Research: Atmospheres*, 118, 5992–6001, 2013.
- Roos, P. C. and Hulscher, S. J. M. H.: Large-scale seabed dynamics in offshore morphology: Modeling human intervention, *Reviews of Geophysics*, 41, 2002RG000 120, <https://doi.org/10.1029/2002RG000120>, 2003.
- Rouse, H.: Modern conceptions of the mechanics of fluid turbulence, *Transactions of the American Society of Civil Engineers*, 102, 463–505, 1937.
- Ryabinin, V., Barbière, J., Haugan, P., Kullenberg, G., Smith, N., McLean, C., Troisi, A., Fischer, A., Aricò, S., Aarup, T., Pissierssens, P., Visbeck, M., Enevoldsen, H. O., and Rigaud, J.: The UN Decade of Ocean Science for Sustainable Development, *Frontiers in Marine Science*, Volume 6 - 2019, <https://doi.org/10.3389/fmars.2019.00470>, 2019.
- Sánchez-Arcilla, A., Sierra, J. P., Brown, S., Casas-Prat, M., Nicholls, R. J., Lionello, P., and Conte, D.: A review of potential physical impacts on harbours in the Mediterranean Sea under climate change, *Regional environmental change*, 16, 2471–2484, 2016.
- Seabergh, W. C. and Kraus, N. C.: Progress in management of sediment bypassing at coastal inlets: natural bypassing, weir jetties, jetty spurs, and engineering aids in design, *Coastal Engineering Journal*, 45, 533–563, 2003.
- Seminara, G.: *River, coastal and estuarine morphodynamics*, Springer Science & Business Media, ISBN 978-3-642-07530-8, <https://doi.org/10.1007/978-3-662-04571-8>, 2001.

- Sharmar, V. D., Markina, M. Y., and Gulev, S. K.: Global Ocean Wind-Wave Model Hindcasts Forced by Different Reanalyzes: A Comparative Assessment, *Journal of Geophysical Research: Oceans*, 126, e2020JC016710, <https://doi.org/10.1029/2020JC016710>, e2020JC016710 2020JC016710, 2021.
- Shchepetkin, A. F. and McWilliams, J. C.: The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, *Ocean modelling*, 9, 347–404, <https://doi.org/10.1016/j.ocemod.2004.08.002>, 2005.
- Shirinov, S., Federico, I., Bonamano, S., Causio, S., Biocca, N., Piermattei, V., Piazzolla, D., Alessandri, J., Mentaschi, L., Coppini, G., Marcelli, M., and Pinardi, N.: Modelling vegetation-induced wave attenuation: the impact of sea-grass seasonal variability and biomechanical flexibility, *Natural Hazards and Earth System Sciences*, 25, 3737–3758, <https://doi.org/10.5194/nhess-25-3737-2025>, 2025.
- Smagorinsky, J.: General circulation experiments with the primitive equations: I. The basic experiment, *Monthly weather review*, 91, 99–164, 1963.
- Son, M. and Hsu, T.-J.: The effects of flocculation and bed erodibility on modeling cohesive sediment resuspension, *Journal of Geophysical Research: Oceans*, 116, <https://doi.org/https://doi.org/10.1029/2010JC006352>, 2011.
- Soriano-González, J., Urrego, E. P., Sòria-Perpinyà, X., Angelats, E., Alcaraz, C., Delegido, J., Ruíz-Verdú, A., Tenjo, C., Vicente, E., and Moreno, J.: Towards the combination of C2RCC processors for improving water quality retrieval in inland and coastal areas, *Remote Sensing*, 14, 1124, 2022.
- Soulsby, R.: Dynamics of marine sands, Thomas Telford Publishing, <https://doi.org/10.1680/doms.25844>, 1997.
- Soulsby, R. L. and Whitehouse, R. J.: Threshold of sediment motion in coastal environments, in: Pacific Coasts and Ports' 97: Proceedings of the 13th Australasian Coastal and Ocean Engineering Conference and the 6th Australasian Port and Harbour Conference; Volume 1, pp. 145–150, Centre for Advanced Engineering, University of Canterbury Christchurch, NZ, 1997.
- Staneva, J., Alari, V., Breivik, Ø., Bidlot, J.-R., and Mogensen, K.: Effects of wave-induced forcing on a circulation model of the North Sea, *Ocean Dynamics*, 67, 81–101, 2017.
- Stratigaki, V., Manca, E., Prinos, P., Losada, I. J., Lara, J. L., Sclavo, M., Amos, C. L., Cáceres, I., and and, A. S.-A.: Large-scale experiments on wave propagation over *Posidonia oceanica*, *Journal of Hydraulic Research*, 49, 31–43, <https://doi.org/10.1080/00221686.2011.583388>, 2011.
- Struiksmā, N., Olesen, K., Flokstra, C., and De Vriend, H.: Bed deformation in curved alluvial channels, *Journal of Hydraulic Research*, 23, 57–79, 1985.
- Suzuki, T. and Dijkstra, J.: Wave propagation over strongly varying topography: cliffs and vegetation, in: 32nd Congress of IAHR, the international Association of Hydraulic Engineering & Research, Venice, Italy, edited by Prince Sultan Bin Abdulaziz, pp. 1–10, Corila, ISBN 8889405066, <https://resolver.tudelft.nl/uuid:64cbabbf-125d-4abf-808b-e94e0133b132>, 2007.
- Suzuki, T., Zijlema, M., Burger, B., Meijer, M. C., and Narayan, S.: Wave dissipation by vegetation with layer schematization in SWAN, *Coastal Engineering*, 59, 64–71, <https://doi.org/10.1016/j.coastaleng.2011.07.006>, 2012.

- Syvitski, J. P., Slingerland, R. L., Burgess, P., Meiburg, E., Murray, A. B., Wiberg, P., Tucker, G., and Voinov, A. A.: Morphodynamic models: an overview, CRC Press London, Taylor & Francis Group, 2010.
- Sánchez-González, J. F., Sánchez-Rojas, V., and Memos, C. D.: Wave attenuation due to *Posidonia oceanica* meadows, *Journal of Hydraulic Research*, 49, 503–514, <https://doi.org/10.1080/00221686.2011.552464>, 2011.
- Takaya, Y., Bidlot, J.-R., Beljaars, A. C., and Janssen, P. A.: Refinements to a prognostic scheme of skin sea surface temperature, *Journal of Geophysical Research: Oceans*, 115, 2010.
- Talmon, A., Struiksmas, N., and Van Mierlo, M.: Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes, *Journal of hydraulic research*, 33, 495–517, 1995.
- Tambroni, N. and Seminara, G.: Are inlets responsible for the morphological degradation of Venice Lagoon?, *Journal of Geophysical Research: Earth Surface*, 111, <https://doi.org/10.1029/2005JF000334>, 2006.
- Tambroni, N., Bolla Pittaluga, M., and Seminara, G.: Laboratory observations of the morphodynamic evolution of tidal channels and tidal inlets, *Journal of Geophysical Research: Earth Surface*, 110, <https://doi.org/10.1029/2004JF000243>, 2005.
- Tambroni, N., Ferrarin, C., and Canestrelli, A.: Benchmark on the numerical simulations of the hydrodynamic and morphodynamic evolution of tidal channels and tidal inlets, *Continental Shelf Research*, 30, 963–983, <https://doi.org/10.1016/j.csr.2009.12.005>, the Coastal Morphodynamics of Venice Lagoon and its Inlets, 2010.
- Tassi, P. and Villaret, C.: Sisyph v6. 3 user's manual, Recherche et développement, Électricité de France: Chatou, France, 2014.
- Tassi, P., Benson, T., Delinares, M., Fontaine, J., Huybrechts, N., Kopmann, R., Pavan, S., Pham, C.-T., Taccone, F., and Walther, R.: GAIA - a unified framework for sediment transport and bed evolution in rivers, coastal seas and transitional waters in the TELEMAC-MASCARET modelling system, *Environmental Modelling & Software*, 159, 105544, <https://doi.org/10.1016/j.envsoft.2022.105544>, 2023.
- Telesca, L., Belluscio, A., Criscoli, A., Ardizzone, G., Apostolaki, E. T., Frascchetti, S., Gristina, M., Knittweis, L., Martin, C. S., Pergent, G., Alagna, A., Badalamenti, F., Garofalo, G., Gerakaris, V., Louise Pace, M., Pergent-Martini, C., and Salomidi, M.: Seagrass meadows (*Posidonia oceanica*) distribution and trajectories of change, *Scientific Reports*, 5, 12505, <https://doi.org/10.1038/srep12505>, 2015.
- The MPI Forum, C.: MPI: a message passing interface, in: *Proceedings of the 1993 ACM/IEEE Conference on Supercomputing*, Supercomputing '93, p. 878–883, Association for Computing Machinery, New York, NY, USA, ISBN 0818643404, <https://doi.org/10.1145/169627.169855>, 1993.
- Tolman, H.: Validation of WAVEWATCH III version 1.15 for a global domain, Tech. rep., NOAA/NWS/NCEP/OMB Tech. Note 213, 2002.
- Tolman, H. L.: Effects of numerics on the physics in a third-generation wind-wave model, *Journal of physical Oceanography*, 22, 1095–1111, 1992.
- Tolman, H. L. et al.: User manual and system documentation of WAVEWATCH III TM version 3.14, Technical note, MMAB contribution, 276, 2009.

- Touchette, B. W. and Burkholder, J. M.: Overview of the physiological ecology of carbon metabolism in seagrasses, *Journal of experimental marine biology and ecology*, 250, 169–205, 2000.
- Trotta, F., Federico, I., Pinardi, N., Coppini, G., Causio, S., Jansen, E., Iovino, D., and Masina, S.: A relocatable ocean modeling platform for downscaling to shelf-coastal areas to support disaster risk reduction, *Frontiers in Marine Science*, 8, 642 815, 2021.
- Umgiesser, G., Canu, D. M., Cucco, A., and Solidoro, C.: A finite element model for the Venice Lagoon. Development, set up, calibration and validation, *Journal of Marine Systems*, 51, 123–145, 2004.
- Vallis, G. K.: *Atmospheric and oceanic fluid dynamics*, Cambridge University Press, ISBN 978-1-107-06550-5, <https://doi.org/10.1017/9781107588417>, 2017.
- Van Rijn, L. C.: Sediment transport, part III: bed forms and alluvial roughness, *Journal of hydraulic engineering*, 110, 1733–1754, 1984.
- Van Rijn, L. C.: *Principles of sediment transport in rivers, estuaries and coastal seas*, ”, 1993.
- Van Rijn, L. C.: Unified View of Sediment Transport by Currents and Waves. I: Initiation of Motion, Bed Roughness, and Bed-Load Transport, *Journal of Hydraulic Engineering*, 133, 649–667, [https://doi.org/10.1061/\(ASCE\)0733-9429\(2007\)133:6\(649\)](https://doi.org/10.1061/(ASCE)0733-9429(2007)133:6(649)), 2007.
- Varghese, D., Piermattei, V., Madonia, A., and Marcelli, M.: Tiber River-Driven Chlorophyll-a and Total Suspended Matter Dynamics and Their Impacts along the Central Tyrrhenian Sea Coast: A Sentinel-2 Approach, *International Journal of Applied Earth Observation and Geoinformation*, 134, 104 161, <https://doi.org/10.1016/j.jag.2024.104161>, 2024.
- Vassallo, P., Paoli, C., Rovere, A., Montefalcone, M., Morri, C., and Bianchi, C. N.: The value of the seagrass *Posidonia oceanica*: A natural capital assessment, *Marine Pollution Bulletin*, 75, 157–167, <https://doi.org/10.1016/j.marpolbul.2013.07.044>, 2013.
- Verri, G., Barletta, I., Pinardi, N., Federico, I., Alessandri, J., and Coppini, G.: Shelf slope, estuarine dynamics and river plumes in a z^* vertical coordinate, unstructured grid model, *Ocean Modelling*, 184, 102 235, <https://doi.org/10.1016/j.ocemod.2023.102235>, 2023.
- Vetrano, A., Napolitano, E., Iacono, R., Schroeder, K., and Gasparini, G. P.: Tyrrhenian Sea circulation and water mass fluxes in spring 2004: Observations and model results, *Journal of Geophysical Research: Oceans*, 115, <https://doi.org/10.1029/2009JC005680>, 2010.
- Vettori, D., Pezzutto, P., Bouma, T. J., Shahmohammadi, A., and Manes, C.: On the wave attenuation properties of seagrass meadows, *Coastal Engineering*, 189, 104 472, <https://doi.org/10.1016/j.coastaleng.2024.104472>, 2024.
- Vettori, D., Giordana, F., and Manes, C.: Turbulence enhances wave attenuation of seagrass in combined wave–current flows, *Proceedings of the National Academy of Sciences*, 122, e2414150 122, <https://doi.org/10.1073/pnas.2414150122>, 2025.
- Villaret, C., Hervouet, J.-M., Kopmann, R., Merkel, U., and Davies, A. G.: Morphodynamic modeling using the Telemac finite-element system, *Computers & Geosciences*, 53, 105–113, 2013a.

- Villaret, C., Hervouet, J.-M., Kopmann, R., Merkel, U., and Davies, A. G.: Morphodynamic modeling using the Telemac finite-element system, *Computers & Geosciences*, 53, 105–113, <https://doi.org/10.1016/j.cageo.2011.10.004>, 2013b.
- Volpe, V., Silvestri, S., and Marani, M.: Remote sensing retrieval of suspended sediment concentration in shallow waters, *Remote sensing of Environment*, 115, 44–54, 2011.
- Von Schuckmann, K., Le Traon, P., Menna, M., Martellucci, R., Notarstefano, G., Mauri, E., Gerin, R., Pacciaroni, M., Bussani, A., Pirro, A., et al.: Copernicus Ocean state report, issue 6, *Journal of Operational Oceanography*, 15, 1–220, 2022.
- Von Storch, H. and Woth, K.: Storm surges: perspectives and options, *Sustainability Science*, 3, 33–43, <https://doi.org/10.1007/s11625-008-0044-2>, 2008.
- Wang, L., Tomas, F., and Mueller, R. S.: Nutrient enrichment increases size of *Zostera marina* shoots and enriches for sulfur and nitrogen cycling bacteria in root-associated microbiomes., *FEMS microbiology ecology*, <https://doi.org/10.1093/femsec/fiaa129>, 2020.
- Wang, P. and Sheng, J.: A comparative study of wave-current interactions over the eastern Canadian shelf under severe weather conditions using a coupled wave-circulation model, *Journal of Geophysical Research: Oceans*, 121, 5252–5281, 2016.
- Wang, Q.: The finite element ocean model and its aspect of vertical discretization, Ph.D. thesis, Universität Bremen, 2007.
- Wang, Q., Danilov, S., and Schröter, J.: Finite element ocean circulation model based on triangular prismatic elements, with application in studying the effect of topography representation, *Journal of Geophysical Research: Oceans*, 113, <https://doi.org/10.1029/2007JC004482>, 2008.
- Wang, Q., Danilov, S., Sidorenko, D., Timmermann, R., Wekerle, C., Wang, X., Jung, T., and Schröter, J.: The Finite Element Sea Ice-Ocean Model (FESOM) v. 1.4: formulation of an ocean general circulation model, *Geoscientific Model Development*, 7, 663–693, <https://doi.org/10.5194/gmd-7-663-2014>, 2014.
- Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., and Arango, H. G.: Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, *Computers & geosciences*, 34, 1284–1306, 2008.
- Warren, I. and Bach, H.: MIKE 21: a modelling system for estuaries, coastal waters and seas, *Environmental software*, 7, 229–240, 1992.
- Wong, P. P., Losada, I. J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K. L., Saito, Y., Sallenger, A., et al.: Coastal systems and low-lying areas, *Climate change*, 2104, 361–409, 2014.
- Wu, L., Chen, C., Guo, P., Shi, M., Qi, J., and Ge, J.: A FVCOM-based unstructured grid wave, current, sediment transport model. I. Model description and validation, *Journal of Ocean University of China*, 10, 1–8, <https://doi.org/10.1007/s11802-011-1788-3>, 2011.
- WW3DG: User manual and system documentation of WAVEWATCH III, NOAA/NWS/NCEP/MMAB, College Park, MD, USA, <https://polar.ncep.noaa.gov/waves/wavewatch/>, accessed: 2025-07-10, 2019.
- Xia, H., Xia, Z., and Zhu, L.: Vertical variation in radiation stress and wave-induced current, *Coastal engineering*, 51, 309–321, 2004.

- Xia, M., Mao, M., and Niu, Q.: Implementation and comparison of the recent three-dimensional radiation stress theory and vortex-force formalism in an unstructured-grid coastal circulation model, *Estuarine, Coastal and Shelf Science*, 240, 106 771, 2020.
- Yalin, M. S.: On the determination of ripple length, *Journal of the Hydraulics Division*, 103, 439–442, 1977.
- YAMAGUCHI, M.: Approximate expressions for integral properties of the JONSWAP spectrum, *Doboku Gakkai Ronbunshu*, 1984, 149–152, 1984.
- Yankovsky, A. E. and Chapman, D. C.: A simple theory for the fate of buoyant coastal discharges, *Journal of Physical oceanography*, 27, 1386–1401, 1997.
- Yen, C.-I. and Lee, K. T.: Bed topography and sediment sorting in channel bend with unsteady flow, *Journal of Hydraulic Engineering*, 121, 591–599, 1995.
- Young, I. R. and Ribal, A.: Multiplatform evaluation of global trends in wind speed and wave height, *Science*, 364, 548–552, 2019.
- Zambon, J. B., He, R., and Warner, J. C.: Investigation of hurricane Ivan using the coupled ocean–atmosphere–wave–sediment transport (COAWST) model, *Ocean Dynamics*, 64, 1535–1554, <https://doi.org/10.1007/s10236-014-0777-7>, 2014.
- Zekkos, D., Zalachoris, G., Alvertos, A., Amatyia, P., Blunts, P., Clark, M., Dafis, S., Farmakis, I., Ganas, A., Hille, M., et al.: The September 18-20 2020 Medicane Ianos Impact on Greece-Phase I Reconnaissance Report, 2020.
- Zhang, X., Lin, P., Gong, Z., Li, B., and Chen, X.: Wave Attenuation by *Spartina alterniflora* under Macro-Tidal and Storm Surge Conditions, *Wetlands*, 40, <https://doi.org/10.1007/s13157-020-01346-w>, 2020.
- Zhang, Y. and Baptista, A. M.: SELFIE: A semi-implicit Eulerian–Lagrangian finite-element model for cross-scale ocean circulation, *Ocean modelling*, 21, 71–96, <https://doi.org/10.1016/j.ocemod.2007.11.005>, 2008.
- Zhang, Y. J., Ye, F., Stanev, E. V., and Grashorn, S.: Seamless cross-scale modeling with SCHISM, *Ocean Modelling*, 102, 64–81, <https://doi.org/10.1016/j.ocemod.2016.05.002>, 2016.
- Zijlema, M., Stelling, G., and Smit, P.: SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters, *Coastal Engineering*, 58, 992–1012, <https://doi.org/10.1016/j.coastaleng.2011.05.015>, 2011.
- Zupo, V., Buia, M., and Mazzella, L.: A Production Model for *Posidonia oceanica* based on Temperature, *Estuarine, Coastal and Shelf Science*, 44, 483–492, <https://doi.org/10.1006/ecss.1996.0137>, 1997.
- Zyserman, J. A. and Fredsøe, J.: Data analysis of bed concentration of suspended sediment, *Journal of Hydraulic Engineering*, 120, 1021–1042, 1994.