



Toward a more realistic modelling of coastal hydrodynamics: impact of the boundary conditions in the three-dimensional phase-resolving model Symphonie 3.8.9

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Abstract. This study focuses on improving wave boundary conditions for phase-resolving coastal simulations using the three-dimensional non-hydrostatic SYMPHONIE model deployed on the rocky beach of Ars-en-Ré (France), located on the exposed northwestern coast of Ré Island. With regard to waves leaving the numerical domain, a new radiative condition scheme is proposed. With regard to waves entering the domain, two approaches for forcing offshore boundary conditions are compared: using direct measurements and downscaling from larger-scale, lower-resolution spectral wave models. A particular frequency de-coherence procedure is applied to reconstruct the phase-resolving boundary signal from the directional wave spectrum.

The model's performance is evaluated against a comprehensive hydrodynamic and bathymetric field campaign conducted during the winter of 2020–2021. Comparisons with in situ observations demonstrate that both configurations successfully reproduce the variability of significant wave heights and frequency spectra across the nearshore zone, as well as the main directional wave transformation from offshore to nearshore. While both offshore-forcing strategies provide realistic results, uncertainties associated with the incident spectral forcing and its phase-resolving reconstruction, the numerical representation of bathymetry and dissipation processes remain a major source of model variability.

1 Introduction

Accurate, fine-scale modelling of the sea state and of coastal hydrodynamics is crucial for public policy decision-making, and for operational forecasting such as marine submersion or warning bulletins (Jourdan et al., 2023). The actual sea level rise and the suggested intensification of storms (Oppenheimer et al., 2019; Knutson et al., 2021) combined with natural subsidence (Wöppelmann and Marcos, 2016; Dinar et al., 2021; Gravelle et al., 2023) accentuates the need for setting simulation grids



refined at higher resolution in order to better describe local hydrodynamics patterns to adapt defence structures and to develop effective warning systems.

20 For now, operational storm surge models (Michaud et al., 2015; Filippini et al., 2024) are generally based on circulation models, often barotropic, coupled with spectral wave models (e.g. WAVEWATCH III (Group, 2019), SWAN (Booij et al., 1999)), using Vortex-Force equations (McWilliams et al., 2004; Smith, 2006; Ardhuin et al., 2008; Bennis et al., 2011; Michaud et al., 2012; Martins et al., 2022) or Radiation Stress formalism (Longuet-Higgins and Stewart, 1962, 1964). Operational implementations may rely either on separate circulation and spectral wave models exchanging information through an external
 25 coupler, such as OASIS (Valcke et al., 2015), or on tightly integrated modelling systems in which the two components interact internally. The latter include unstructured systems such as SCHISM-WWM, used in operational services such as OPENCoastS (Oliveira et al., 2021). Regardless of the coupling architecture, these approaches remain intrinsically limited by their statistical representation of the wave field. Spectral wave models describe the evolution of the wave energy spectrum, from which bulk parameters such as significant wave height, mean wave period, and mean wave direction are derived. Consequently, coupled
 30 circulation–spectral wave systems primarily represent the slowly varying contributions to coastal sea level, including tides, storm surges, and wave setup. They do not explicitly resolve individual waves, infragravity (IG) motions (Bertin et al., 2018), or high-frequency shoreline processes such as swash and run-up, although these processes can be critical for predicting coastal flooding and overtopping.

An alternative is to use phase-resolving models able to describe the wave field dynamics at the scale of an individual wave
 35 (e.g. Kirby et al., 1998; Smit et al., 2010; Zijlema et al., 2011; Roeber and Cheung, 2012; McCall et al., 2014; Marsaleix et al., 2019; Marchesiello et al., 2021; Richard, 2021). Forced by larger spectral models and circulation models at regional scales, phase-resolving models have the potential to represent each driving physical process involved in coastal flooding from the coastal surge to the wave impact (Seyfried et al., 2024; Imbertie, 2024). With the continuous increase in computing resources and advances in numerical schemes (Richard, 2021; Mihami et al., 2022), phase-resolving models have the potential to replace
 40 older generations of models for many operational marine flooding forecasting (e.g. Torres-Freyermuth et al., 2012; Nicolae-Lerma et al., 2017; Bellafont et al., 2018; de Beer et al., 2021; Pinault et al., 2022; Lange et al., 2024).

Phase-resolving wave models deployed in nearshore areas must account for wave non-linearity and dispersion. In most cases, this is achieved using either Boussinesq-based depth-averaged (2DH) models or depth-resolved (3D multi-layer) models based on various forms of the Non-Linear Shallow Water Equations (NLSWE) including a non-hydrostatic correction. This
 45 latter type of model allows for a more comprehensive description of the vertical structure of the flow, which is of primary importance in the wave-driven momentum balance and wave transformation in the presence of vertical shear and/or complex seabeds such as rocky, coral or vegetated areas. However, despite the promising potential of depth- and phase-resolving models, full realistic 3D applications remain scarce (e.g., Marsaleix et al., 2020; Marchesiello et al., 2021; Treillou et al., 2024), and even more with realistic offshore boundary conditions over large domains that take into account general circulation, tides and
 50 offshore waves possibly varying along each offshore boundary. Most existing studies, typically limited to domains of a few kilometers, are forced at a single point or along part of the offshore boundary using one or multiple stationary directional spectra and time series of sea level originating from in situ measurements or coarser models. At the lateral boundaries (that are



outgoing borders only), they either specify sponge layers to absorb the wave fields (Vasarmidis et al., 2021, 2024), or apply lateral periodic boundary conditions (e.g. Treillou et al., 2024) to avoid the need for large domains and to keep computational costs manageable. With the continuous increase in computing resources, much larger domains can now be targeted, opening the possibility of embedding phase-resolving coastal-scale simulations within regional to basin-scale phase-averaging frameworks. The incorporation of the spatial variability of offshore forcing at the boundaries becomes a crucial issue, so that downscaled simulations remain dynamically consistent with larger-scale circulation and wave fields.

The present investigation is a contribution to the ongoing refinement of coastal wave modelling techniques, keeping in mind a wide range of applications from coastal engineering to climate change impact assessment. The precise objective of this work is to discuss and solve the critical issue of boundary conditions for realistic coastal wave modelling. Specifically, we compare two approaches for forcing offshore boundary wave conditions into coastal phase-resolving models: (1) using direct eulerian field measurements and (2) downscaling from a larger-scale spectral wave model. The tested model is SYMPHONIE (Marsaleix et al., 2019), in its phase-resolving non-hydrostatic configuration, applied on a real rocky coastal environment. Working on a rocky seabed where the bathymetry is known and fixed offers a major advantage for model evaluation compared to sandy study sites, where the bathymetry can evolve rapidly and hence become inconsistent with the one used in the model.

The paper is structured as follows: Sections 2 and 3 describe the field site and the experiments, respectively, providing context for the observational data used in this study. Section 4 details the model, with particular emphasis on recent developments in boundary condition implementation. Section 5 presents the results of the numerical configurations of the nearshore-scale phase-resolving model and the comparisons with the observations. Sections 6 and 7 are dedicated to discussion and conclusions, respectively, synthesizing our findings and outlining directions for future research.

2 Study site

The Ré Island, located off the western coast of France (Fig. 1a), has a long history of marine floodings (Chauveau et al., 2011; Breilh et al., 2014; Athimon and Maanan, 2018). The impact of Storm Xynthia, in February 2010 (Chauveau et al., 2011; Bertin et al., 2012) prompted the French government to improve marine submersion forecasting, leading to the Homonim project (Jourdan et al., 2023) co-led by the French Navy Hydrographic and Oceanographic Office (Shom) and the French national meteorological service (Météo-France). As part of this initiative, a comprehensive oceanographic and bathymetric measurement campaign called RiCoRé was conducted during the winter of 2020–2021 to enhance understanding of flooding processes for this vulnerable area.

The study site is an 8-km beach located in the northwest of the island, between Ars-en-Ré and Saint-Clément-des-Baleines (Fig. 1). This nearly natural beach comprises a vast, flat rocky platform with an approximate slope of 0.001, emerging over about 1 km under spring tides. The platform consists of marl and argillaceous limestone, followed by a narrow sand beach-dune system and a dike protecting inland villages and salt marshes. The alongshore platform profile is heterogeneous, featuring remnants of fish locks and several canyons (Fig. 1b). The coastline is subject to a semi-diurnal tidal regime, with a maximum tidal range of approximately 5.7 m along the coast. Waves mainly originate from the West or North-West, with exposure to

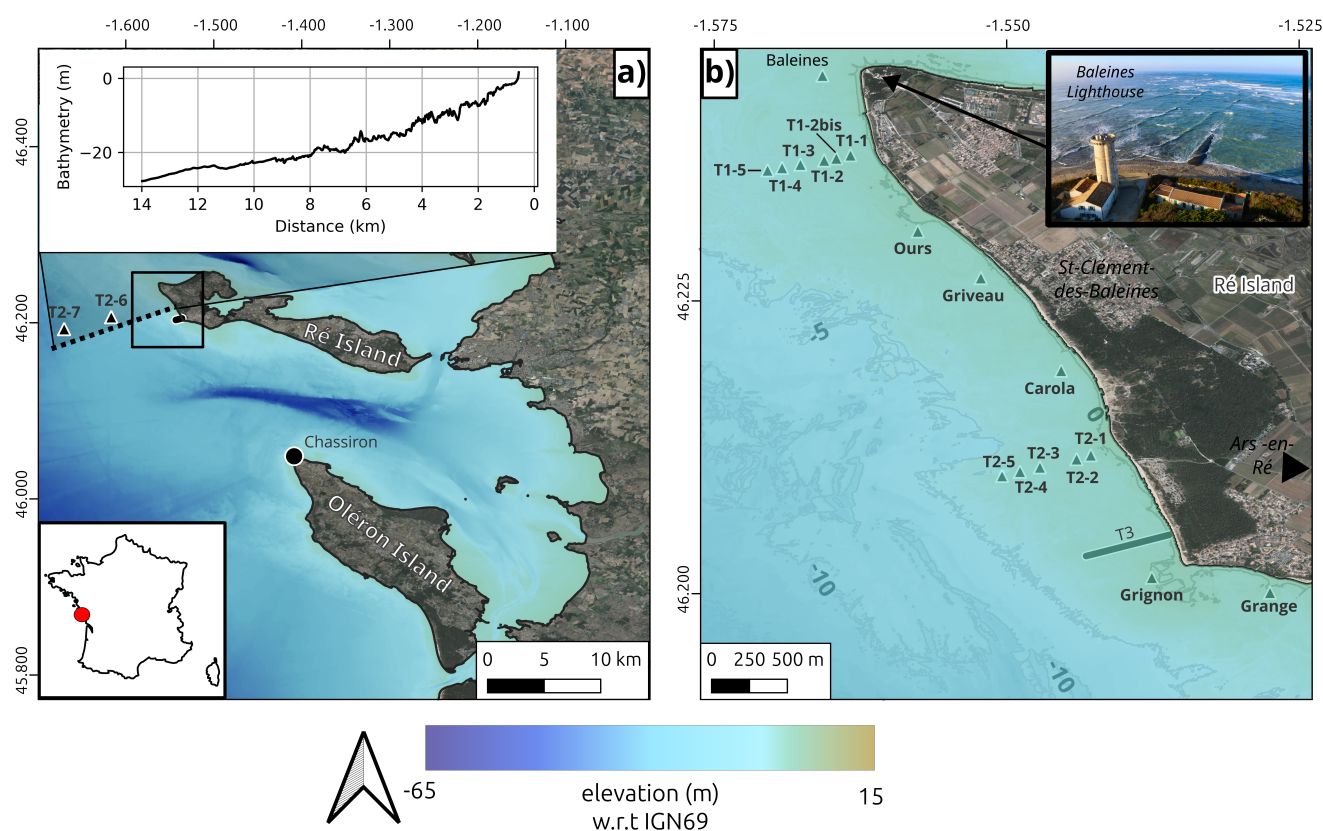


Figure 1. Bathymetry (below mean level) and aerial pictures (BD ORTHO® IGN) of the Pertuis-Charentes area (a) and the surroundings of the west Coast of Ré Island (b). Mooring positions are indicated in black triangles. A representative cross-shore alti-bathymetric profile in the shoreface of the experimental zone is indicated at top right of a). In the inset of b), a photograph of the crossed-seas taken from the Baleines lighthouse with an arrow indicating the lighthouse's position.



strong storm waves that can reach 9 m offshore at the closest offshore wave buoy "Oléron Large" deployed by 50 m water depth (Ciaran storm, November 2023, (Kergadallan, 2024)). The combination of variable beach orientation, variable incoming wave fields and complex bathymetry make the studied site a relevant benchmark to assess the robustness of wave dynamics in 3D phase-resolving models.

90 3 Field campaign

3.1 Bathymetry

Bathymetric and topographic measurements were conducted using LiDAR acquisitions on the foreshore and multibeam sounders offshore, enabling the generation of a 5 m high-resolution Topo-Bathymetric Digital Terrain Model (TDBDMs, dataset available from (Shom, 2024)) in spring and autumn 2020 (Fig. 1). Additional topographic surveys were conducted along transect
 95 T3 (Le Goff Le Gourriec et al., 2022).

3.2 Instrumental setup

Between November 2020 and May 2021, an extensive oceanographic campaign was conducted off Ars-en-Ré beach, deploying 39 moored stations equipped with various sensors, including acoustic wave and current profilers, single-point current meters, pressure gauges and directional wave buoys. To better understand the analysis, the measurement campaign is divided into two
 100 main periods: (1) LEG1 (from 11/16/2020 to 01/13/2021) and (2) LEG2 (from 01/14/2021 to 03/31/2021). A short period LEG3 (from 01/11/2021 to 01/15/2021) that straddles LEG1 and LEG2. LEG1 corresponds to the first acquisition period for the sensors on the foreshore, LEG2 to the second acquisition period for the sensors on the foreshore after the battery change, and LEG3 is one week with 23 additional instruments provided by university partners.

The moorings were positioned along three main cross-shore transects named T1, T2, and T3. Transect T1 was located near
 105 the Baleines lighthouse in the northern sector, T2 in the central part of the beach, and T3 in the southern sector (Fig. 1b, Appendix A). T1 and T2 instruments recorded pressure, currents and water level data from the inner shelf to the upper beach during the full campaign, with seven measurement points deployed along each transect. Transect T3 was added for a focused survey over a single week during LEG3, consisting of 17 pressure sensors (labelled offshore to nearshore as PT1 to PT4, then G00 to G12) spaced approximately 20 m apart and a spatial high-resolution velocity measurement station named UHR (Ultra
 110 High Resolution) combining three point current meters and two current profilers. Detailed information on the instrumentation can be found in Appendix A, Table A1. Incoming wave conditions were measured offshore the T2 transect, using a Datawell directional wave buoy (T2-6 in Fig. 1B). An additional offshore sea level measurement point (Acoustic Wave and Current Profiler deployed at T2-7) was used to validate the low-frequency model, see Section 4.3.2.

For the purpose of the present study, we will focus on a subset of relevant data including the pressure sensors, the wave buoy
 115 in T2-6 and the current profilers in T2-7 and UHR during LEG3.



3.3 Data processing

All the collected data were processed using a classical oceanographic data processing method based on the linear reconstruction method (Bishop and Donelan, 1987) as described in Seyfried et al. (2024). Free surface spectra were reconstructed from bottom pressure measurements using linear theory, using a high cut-off frequency of 0.25 Hz and a separation between IG and gravity waves at $f_{min} = f_p/2$ with f_p the offshore peak frequency measured by the wave buoy T2-6. The calculation of integrated wave parameters was then performed between f_{min} and $f_{max} = 0.2$ Hz. Model outputs used for field/model comparisons were processed with the same methodology.

The classical linear reconstruction approach was retained to ensure consistency with standard coastal field-data processing practices and a homogeneous treatment of observations and model outputs. Although more recent non-linear surface reconstruction methods may improve the reconstruction of the high-frequency part of the spectrum (Bonneton et al., 2018; Martins et al., 2020), the spectral comparisons presented here are limited to frequencies below 0.2 Hz, where differences between reconstruction methods are expected to remain small under the conditions considered. Their influence on the frequency-integrated wave parameters analysed in this study is therefore also expected to be limited. Nevertheless, such methods could be evaluated in future work, ideally using colocated pressure and free-surface elevation measurements.

3.4 Field conditions

Figure 2 depicts the wave and wind conditions observed during LEG1 and LEG2. The incident swells were from West or West-North West with significant wave height comprised between 0.5 and 8 m and mean period ranging from 3 to 14 s. During the campaign, storms Bella (2020/12/27 to 12/29) and Justine (2021/01/29 to 01/31) reached the field site with respectively significant wave heights of 5.6 and 8 m. Wind conditions are shown from the Chassiron meteorological station on Oléron Island, where wind is measured at the standard 10 m height, rather than from Saint-Clément-des-Baleines on Ré Island, where the 16 m measurement height yields stronger, less directly comparable wind speeds. At Chassiron, wind speed ranged from 2 to 20 m.s⁻¹ over the analysed period with 20 m.s⁻¹ measured during the Bella storm.

4 The numerical model and its boundary conditions

4.1 General equations

The governing equations used in SYMPHONIE have been described in detail in Marsaleix et al. (2019). The non-hydrostatic momentum equation is expressed in a Cartesian coordinate system (O, x, y, z) (where the origin O corresponds to the resting level of the sea surface, Ox and Oy are the horizontal axes with Ox usually pointing toward the shoreline by convention for sake of clarity in the description of the boundary conditions further down, and Oz is the upward vertical axis):

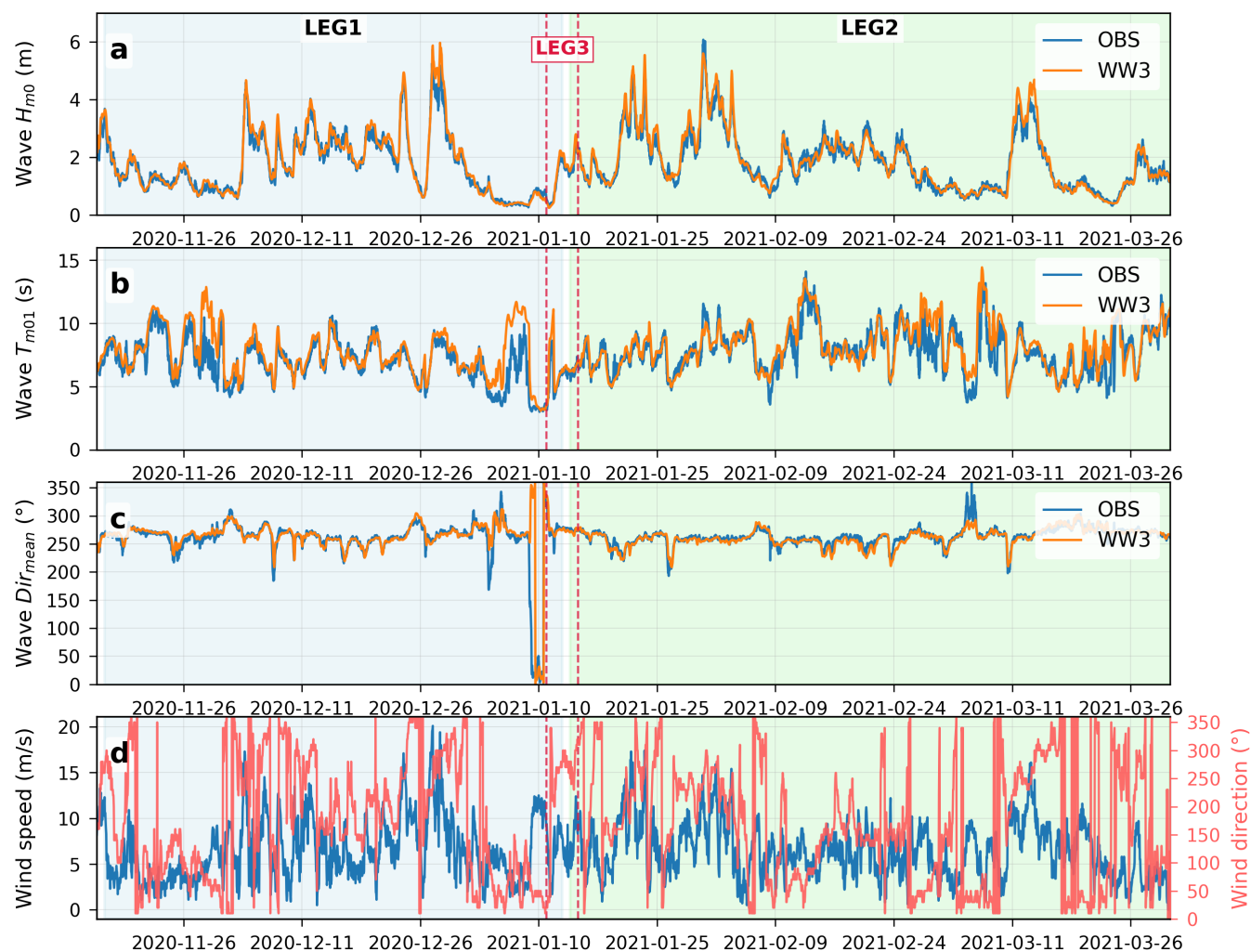


Figure 2. Significant wave height (H_{m0}) (a), mean period (T_{m01}) (b) and mean direction (Dir_{mean}) (c) at T2-6 measured (in blue) and simulated by WAVEWATCH III (WW3 in orange), wind speed (blue) and direction (red) (d) measured at Chassiron (Oléron Island) during LEG1 and LEG2.



$$\begin{cases} \frac{\partial u}{\partial t} = -\frac{\partial uu}{\partial x} - \frac{\partial vu}{\partial y} - \frac{\partial wu}{\partial z} + f_C v - g \frac{\partial \eta}{\partial x} - r \frac{\partial q}{\partial x} + \frac{\partial}{\partial z} \left(K_m \frac{\partial u}{\partial z} \right) + \frac{\partial}{\partial x} \left(\nu_b \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_b \frac{\partial u}{\partial y} \right) - F_u^{BCD} \\ \frac{\partial v}{\partial t} = -\frac{\partial uv}{\partial x} - \frac{\partial vv}{\partial y} - \frac{\partial wv}{\partial z} - f_C u - g \frac{\partial \eta}{\partial y} - r \frac{\partial q}{\partial y} + \frac{\partial}{\partial z} \left(K_m \frac{\partial v}{\partial z} \right) + \frac{\partial}{\partial x} \left(\nu_b \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_b \frac{\partial v}{\partial y} \right) - F_v^{BCD} \end{cases} \quad (1a)$$

$$\quad (1b)$$

145 where (u, v) are the horizontal components of the current, w the vertical velocity, q is the non-hydrostatic pressure times the water density, t the time, g the gravitational acceleration, η the sea surface elevation, K_m the vertical turbulent mixing coefficient, ν_b a momentum diffusion coefficient associated to wave breaking, F^{BCD} the bottom drag force and f_C the Coriolis parameter. The particular form of these equations derives from the ACM approach (Lee et al., 2006), for which (r, α) are optimization parameters proposed by Marsaleix et al. (2019) which leads to the calculation of the non-hydrostatic pressure

150 according to:

$$\frac{1}{\alpha^2} \frac{\partial^2 q}{\partial t^2} = -\frac{\partial}{\partial x} \left(\frac{\partial u}{\partial t} \right)^* - \frac{\partial}{\partial y} \left(\frac{\partial v}{\partial t} \right)^* + \frac{\partial^2 q}{\partial x^2} + \frac{\partial^2 q}{\partial y^2} + \frac{\partial^2 q}{\partial z^2} \quad (2)$$

where $\left(\frac{\partial u}{\partial t} \right)^*$ and $\left(\frac{\partial v}{\partial t} \right)^*$ represent hydrostatic terms of all the terms of the right-hand side of Eqs. (1a) and (1b) that is except $r \frac{\partial q}{\partial x}$ and $r \frac{\partial q}{\partial y}$.

Vertical velocity and surface elevation follow from the continuity assumption:

$$\begin{cases} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \end{cases} \quad (3a)$$

$$155 \quad \begin{cases} \frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x} \int_{-h}^{\eta} u dz - \frac{\partial}{\partial y} \int_{-h}^{\eta} v dz \end{cases} \quad (3b)$$

The vertical turbulent mixing coefficient K_m is calculated from the k-L scheme of Craig and Banner (1994) based on a prognostic equation for turbulent kinetic energy and a diagnostic equation for mixing length.

Following the approach of Kennedy et al. (2000), wave breaking is represented as an additional momentum diffusion coefficient defined as:

$$160 \quad \nu_b = B \nu_0 \quad (4)$$

where ν_0 is a numerical diffusion coefficient constrained by the grid resolution and stability requirements and B a breaking coefficient varying continuously between 0 and 1. The activation of breaking is diagnosed from the local wave steepness $S = \frac{\partial \eta / \partial t}{\sqrt{gH}}$ with H the local water depth. B is equal to 1 when S is greater than a prescribed threshold γ_s , here equal to 0.28. As in Kennedy et al. (2000), B gradually increases from 0 to 1 to avoid an impulsive start of breaking. Once activated, B

165 decreases progressively according to a relaxation equation, allowing wave-breaking effects to persist for a finite time after the breaking criterion is no longer satisfied.

The bottom friction is represented here by a quadratic drag force F^{BCD} , which is written:

$$F_{u,v}^{BCD} = C_D(z) \sqrt{u^2 + v^2} (u, v) \quad (5)$$



with $C_D(z)$ a three-dimensional drag coefficient as traditional smooth-bottom parameterisations of friction using a bottom
 170 shear stress at the base of the water column are hardly able to account for the high roughness of rocky shoreface. Following
 Guélaud Ancilotti et al. (2024), the drag force is applied on several model layers above the bottom depending on the local
 seabed roughness to represent the sub-grid effects of rocky bathymetry. Taken as a whole, fluid/ground interaction is therefore
 more accurately rendered as a volume (canopy) drag force rather than a bed shear stress. At this stage, an average estimate
 (across the entire domain) of the C_D influence height is applied (0.25 m), as this paper focuses solely on the problem of open
 175 boundary conditions; however, the next step in this study will involve a more specific examination of the parameterisation of
 rock macro-roughness.

4.2 Boundary conditions

4.2.1 Review of boundary condition schemes in models

The Flather boundary condition is often used to model long surface waves such as the barotropic tide, allowing to sink mechan-
 180 ical energy without mean level drift (Marsaleix et al., 2006). However, overly lax assumptions about the physics (propagation
 normal to the boundary, strictly progressive wave, no effect of inertial rotation) can lead to radiative property defects, in par-
 ticular with 3D modelling of a realistic wave spectrum and a low-frequency spectrum of ocean circulation.

Another standard type of boundary conditions consists in damping any outgoing signal before it reaches the open boundary.
 This strategy requires identifying the incoming solution, in order to only damp the outgoing field, over a significant portion of
 185 the 3D domain owing to the fact that the damping zone requires many grid points. This can become prohibitive considering
 the complexity of realistic wave field in complex coastal configuration, and will rise additional difficulties when implementing
 two-way couplings between lower-resolution regional grids and phase-averaged circulation models in the future.

Wave modelling on nearly straight beaches often uses the periodic boundary condition (Chen et al., 2003), which im-
 poses equality of fields on both cross-shore lateral boundaries (following O_x axis). It requires that the coastline geometry and
 190 bathymetry reasonably accommodate the periodicity assumption in the alongshore direction (O_y), i.e. that both cross-shore
 lateral boundaries have similar bathymetries. It also imposes a constraint on the wavelength in the O_y direction; the distance
 between the 2 boundaries, D , must correspond to an integer number of wavelengths in the O_y direction, i.e. $D = n \frac{2\pi}{k_y}$ with
 $n = 1, 2, 3, \dots$ which amounts to limiting the possible values of the horizontal wave vector $k = (k_x, k_y)$ in the O_y direction to a
 set of discrete values $k_y = n \frac{2\pi}{D}$ as well as the corresponding propagation angle $\theta = \tan^{-1} [n \frac{2\pi}{D} / k_x]$.

195 4.2.2 A new improved Sommerfeld condition

Considering these limitations, we implement an alternative boundary condition based on a Sommerfeld approach:

$$\eta_t^w - c\eta_x^w = 0 \quad (6)$$

where η^w is the outgoing wave surface elevation. A similar expression is used for the other fields (non-hydrostatic pressure,
 horizontal current components). The apparent phase velocity in the perpendicular direction of the boundary is deduced from



200 the inversion of the condition on points adjacent to the boundary (Orlanski, 1976):

$$c = \eta_t^w / \eta_x^w \quad (7)$$

This condition is known to have shortcomings that are sometimes reported in the literature (Treguier et al., 2001). In particular, the above formulation clearly shows a possibility of singularity whenever η_x^w is close to zero, which formally prevents the phase velocity from being correctly estimated in the vicinity of wave crests and troughs, which in practice concerns a significant part
205 of the phase cycle. An error in phase velocity estimation leads to the generation of spurious waves reflected on the open boundary, and as these in turn influence phase velocity estimation, there is a possibility of error growth due to the feedback of reflected waves on phase velocity estimation. As this process is non-linear, it is difficult to grasp theoretically.

A heuristic solution to the above-mentioned singularity problem is to calculate the expression of Eq. (7) from a series of values allowing the calculation of a weighted average of the phase velocity, the weights P being equal to the square of the
210 slope of the surface elevation to minimize the importance of singular cases, i.e. $c = \sum_{i=1}^N P^i (\eta_t^{w,i} / \eta_x^{w,i}) / \sum_i P^i$ from a series of $i=1, N$ values, with $P = (\eta_x^{w,i})^2$, which finally results in:

$$c = \frac{\sum_{i=1}^N \eta_x^{w,i} \eta_t^{w,i}}{\sum_{i=1}^N (\eta_x^{w,i})^2} \quad (8)$$

The risk of singularity is reduced by taking into consideration a sufficiently large number of samples, so as not to contain only cases where η_x^w is close to zero. However, implementation comes up against a technical obstacle inherent in the characteristics
215 of the models. In this case, the number of temporal samples kept in memory is insufficient in the present model, being in principle limited to 2 in the case of a Leapfrog time-stepping scheme. To overcome this obstacle, the mean is estimated using an alternative method of the *Exponential Moving Average* (EMA) type (Grebekov and Serror, 2014), abbreviated GS14, which involves replacing Eq. (8) by:

$$c = \frac{\langle \eta_x^w \eta_t^w \rangle}{\langle (\eta_x^w)^2 \rangle} \quad (9)$$

220 with:

$$\left\{ \begin{array}{l} \langle \eta_x^w \eta_t^w \rangle (t) = (1 - \alpha_{EMA}) \langle \eta_x^w \eta_t^w \rangle (t - \Delta t) + \alpha_{EMA} \eta_x^w(t) \eta_t^w(t) \end{array} \right. \quad (10a)$$

$$\left\{ \begin{array}{l} \langle \eta_x^w \eta_x^w \rangle (t) = (1 - \alpha_{EMA}) \langle \eta_x^w \eta_x^w \rangle (t - \Delta t) + \alpha_{EMA} \eta_x^w(t) \eta_x^w(t) \end{array} \right. \quad (10b)$$

where Δt is the time step of the model and α_{EMA} a constant determined to limit feedback from reflected waves. These calculations produce an on-line estimate of the low-frequency component of $\eta_x^w \eta_t^w$ and $\eta_x^w \eta_x^w$ (considered here as *the mean*) by analysing the signal over a time lapse preceding the time under consideration, the duration of which depends on the constant
225 α_{EMA} (GS14). When determining the time scale, a compromise must be struck between, on the one hand, the need for a sufficiently long time interval to avoid the aforementioned singularity problem, (i.e., not estimating the phase velocity at the



crest or trough of the wave) and, on the other hand, a time short enough for the phase velocity to correspond accurately to the wave currently leaving the domain and not to older waves. Given the non-linear nature of these processes, determining a theoretical optimum value is *a priori* not straightforward. Instead, an empirical choice has been made here on the basis of results from academic test cases (not presented here) which have led to $\alpha_{EMA} = \frac{\Delta t}{t_{ema}}$ where the time constant t_{ema} (which gives the order of magnitude of the duration explored by the mean EMA, GS14) is set at 2 s, corresponding to approximately one fifth of a typical wave period. The objective is not to suppress physically reflected waves propagating within the computational domain, but rather to improve the estimation of outgoing-wave celerity and thereby the absorbing properties of the open boundary.

4.2.3 Incoming/outgoing duality

The Sommerfeld boundary condition is further implemented to carry the incoming/outgoing signal duality described in Blayo and Debreu (2005) where any boundary condition operator is applied as $\Lambda(\eta) = \Lambda(\eta^{ext})$ where η^{ext} is the external dynamic field entering the domain. In the above equations (Eqs. (6) to (10)), the field η^w represents only the outgoing part of the wave field, which we deduce from η the total field actually represented in the model and η^{ext} from $\eta^w = \eta - \eta^{ext}$. Our total boundary condition is therefore equivalent to $\eta_t - c\eta_x = \eta_t^{ext} - c\eta_x^{ext}$. This way of calculating allows both the entry of waves from the open sea and the reflection-free radiation of outgoing waves. The incoming field η^{ext} contains, on one hand, the wave-related elevation deformation deduced from the frequency and direction spectrum measured or simulated offshore and, on the other hand, the low-frequency signal for surface elevation and currents (the latter subject to a Sommerfeld condition analogous to that for surface elevation, and therefore not detailed here) derived from a regional tidal model.

Finally, we note that the formula of Eq. (9) is based on η^w in order to produce a phase velocity for outgoing waves only (whereas a calculation based on the total field η would be spuriously affected by incoming waves).

4.2.4 Low-frequency sea surface height control

The fact that any constant verifies *de facto* the Sommerfeld boundary condition points to a weakness concerning large scales of time and space (i.e. large enough to be assimilated to constants) on which the Sommerfeld boundary condition has little influence. This long-acknowledged shortcoming can lead to uncontrolled drift of the water level at low frequencies (Blumberg and Kantha, 1985), which has to be corrected by adding to the boundary condition a restoring term towards an arbitrarily defined mean reference level (which in itself can be a moot point if the definition of this reference level is not based on sound theoretical or empirical arguments). In our case, it is expected that a balance will be established through the action of various mechanisms (return current, rip current, coastal drift, etc.), whose 3D and temporal complexity is difficult to grasp. As the simple formulation of the Sommerfeld boundary condition does not contain the elements that would naturally lead to this equilibrium, it is through the restoring term (and the arbitrary choice of the associated restoring time constant) added to the boundary condition, that the model constructs the coast-wide free surface gradient. This filter, which specifically targets low frequencies so as not to interfere with the waves, is based on the term $\langle \eta^w \rangle$, where the symbol $\langle \rangle$ represents an EMA of



η^w using a time constant of 200 s. In practice, the boundary condition is written as:

$$\eta_t^w - c\eta_x^w + \beta^{-1} < \eta^w > = 0 \quad (11)$$

with β^{-1} represents the recall time scale subject to a stability constraint detailed in (Barbot et al., 2022). The possibility of also introducing a restoring term into the equations used inside the domain, in a wide restoring zone of several points close to the open boundaries (Marsaleix et al., 2006), is not taken up here, as it turns out that we are not in a position to know at an affordable cost and with sufficient precision the 2D and 3D hydrodynamic fields coming in over an area as large as a classic restoring zone (see explanations below).

4.2.5 Issues

Due to condition 11, the external forcing η^{ext} must be defined at least on the grid points where the Sommerfeld boundary conditions are calculated, which implies 3 rows of grid points: two to account for the horizontal gradient in the Sommerfeld equation, and a third to address the phase velocity inversion on the neighbouring row (following the method of Orlanski (1976)). Since analogous boundary conditions are applied to the model's 3D variables, similar constraints govern the determination of $(u^{ext}, v^{ext}, q^{ext})$.

By omitting a recall zone as in Marsaleix et al. (2006) and incorporating the additional term in condition 11, we limit the number of grid points where external forcing must be defined. This reduction is crucial for the computational cost of the simulation, as reconstructing continuous signals for $(\eta^{ext}, u^{ext}, v^{ext}, q^{ext})$ from trigonometric series using a relatively large number of directions and frequencies can be computationally expensive.

In our approach, the conversion of the surface elevation spectrum into a continuous time series and its extension to non-hydrostatic velocity and pressure fields relies on linear wave theory. While this theory may be considered overly simplistic in some respects (e.g., due to non-linear wave interactions and complex bathymetry), its application to an extensive recall zone covering a large area could be questionable. Accurately representing the $(\eta^{ext}, u^{ext}, v^{ext}, q^{ext})$ forcing is essential for isolating the outgoing component of the total field $\eta^w = \eta - \eta^{ext}$ and ensuring precise calculations for operations 7 and 6. This, in turn, verifies the dual objectives of boundary conditions: radiating the outgoing field and preserving the accuracy of the incoming field.

4.3 Implementation of boundary conditions on a complex realistic case

SYMPHONIE is implemented around Ars-en-Ré, on a curvilinear grid with a spatial extent of about 10 km in the longshore direction (3000 nodes) and 5 km in the cross-shore direction (1620 nodes) (Fig. 3), with a variable horizontal resolution, from 2.5 m to 5 m offshore, and 10 vertical sigma levels. A simple parameterisation is applied for the frictional terms, using a constant and spatially uniform drag coefficient $C_D = 0.6 \text{ m}^{-1}$ over a uniform roughness-influence layer 0.25 m thick. These values were selected to optimize model performance against field observations over the study period, based on statistical comparisons of wave height of the bias (BIAS), coefficient of determination (R^2), and Willmott index (WI; (Willmott, 1981)) across all transects and sensors.

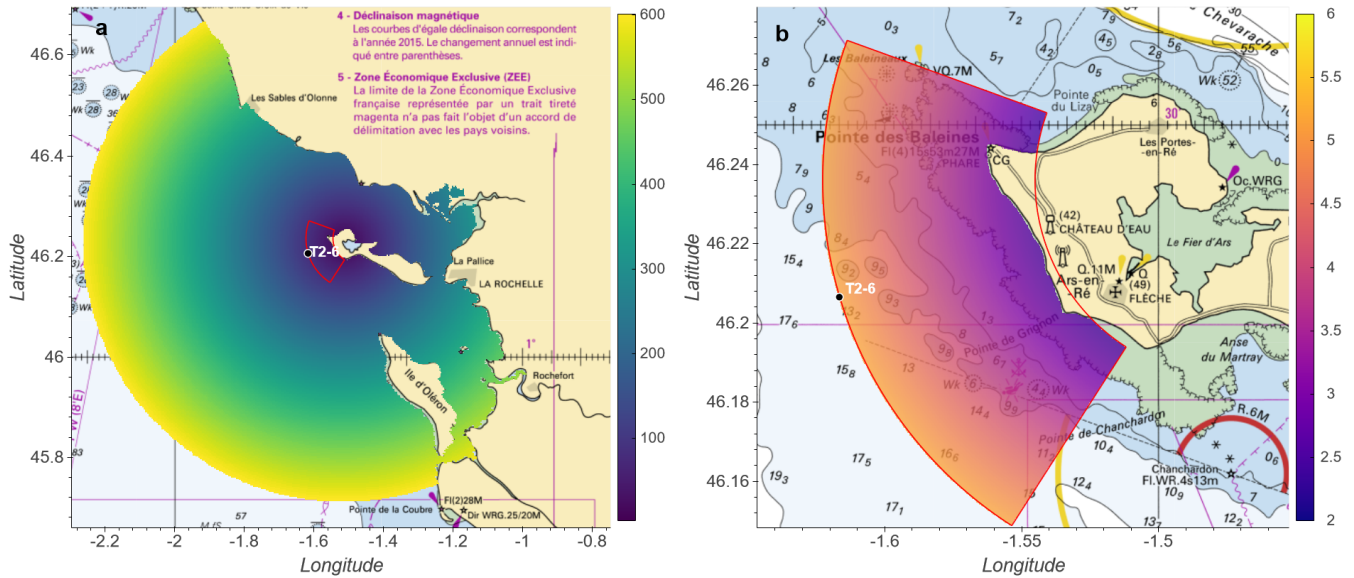


Figure 3. Resolutions (in meter) of the grid of the mother simulation (a) run with Symphonie and of the grid (b) run with phase-resolving version of Symphonie. In red, the domain runs with phase-resolving version of Symphonie.

290 4.3.1 Boundary forcings

The forcing is composed of low-frequency tidal forcing (water level and current) and high-frequency wave forcing in the gravity part of the spectrum cut beyond 0.2 Hz (shorter wavelengths are considered too small compared to the horizontal resolution of the phase-resolving model grid).

4.3.2 Low-frequency fields

295 In this initial phase-resolving simulation, wind forcing is not included since the focus is not on storm periods. Instead, the other low-frequency forcings, that consist of surface elevation and currents, are imposed from hydrostatic barotropic tidal models, using methods similar to those described in Paireud et al. (2008) and Toubanc et al. (2018). A specific horizontal grid has been developed for the present study, based on a polar telescopic grid with variable horizontal resolution, centred on the island of Ré and covering the continental shelf for around 100 km, with a horizontal resolution equal to 600 m on the open circular
 300 offshore boundary where tidal forcing is provided by the FES tidal atlas (Lyard et al., 2021) following the protocol detailed in Paireud et al. (2008) and Toubanc et al. (2018), and a resolution of 20 m at the Ars-en-Ré Beach. A key challenge of the large-scale low-frequency simulation is to provide the mean level of the ocean surface at the boundaries of the phase-resolving high-resolution domain. Considering the weak shoreface slope (Fig. 1), the meso- to macro-tidal sea level fluctuations result in a wide intertidal zone reaching almost a kilometer from the coast, as well as variable wave propagation conditions over the
 305 course of a tidal cycle. The large scale model was validated against sea level observations at the T2-7 AWAC. The mean sea



level is accurately captured by the simulation between November 2020 and May 2021, with a RMSE of 15.7 cm, a bias of 2 cm and correlation coefficient of 0.99.

4.3.3 High-frequency fields

To the above-mentioned low-frequency fields are added high-frequency wave fields, which are either deduced from waves spectra measured at buoy T2-6 located at the centre of the open offshore boundary of the phase-resolving wave model grid (Fig. 3), or supplied by the WW3 phase-averaged wave model implemented on the French continental shelf for the French flooding warning system (NORGAS-UG mesh and configuration described in Michaud et al. (2015)). In both cases, the forcing takes the form of frequency and direction spectra for surface elevation, which are converted into a continuous time series for surface elevation, velocity and non-hydrostatic pressure using the assumptions of linear wave theory (Kinsman, 1965). Note that the IG band is not represented in the WW3 spectral model output and is therefore not directly included in the applied forcing time series.

Buoy forcing has the advantage of being observational, i.e., locally more faithful to reality than a model, and of providing a spectrum with high frequency and directional resolution ($\Delta f = 0.0025$ Hz, $\Delta \theta = 5^\circ$) over the dominant sea-swell frequency band. At lower frequencies, however, the interpretation of the spectral energy becomes more uncertain due to potential mooring and low-frequency response effects. This point information is extrapolated along the entire western open boundary using linear theory, assuming that the amplitude and direction of a wave remain unchanged over the entire boundary, and making arbitrary choices about the initial phase. These assumptions are, of course, debatable, though deemed worthwhile to test as the order of magnitude of bathymetry is roughly the same along the entire western offshore boundary, tending to legitimize the assumption of relative homogeneity of wave spectral characteristics. By contrast, due to the strong variations in bathymetry in the cross-shore direction, the authors deemed it illegitimate to extrapolate the point buoy observation to the lateral cross-shore boundaries to the north and south. The Sommerfeld boundary conditions operate in outgoing mode only.

The second forcing option is based on spectra from a regional configuration of the WW3 phase-averaged wave model forced by the wind from the AROME meteorological model (Seity et al., 2011) and by the offshore waves from the wave spectra of the operational MFWAM global wave configuration (simulation with satellite assimilation) (Aouf et al., 2019). This numerical forcing has the advantage of providing fields over the entire open boundaries of the phase-resolving wave model. In particular, on cross-shore boundaries, a satisfactory representation of the attenuation and refraction of incoming waves (linked to the decrease in bottom depth) is expected. On the other hand, the spectrum simulated by WW3 is less resolved than the buoy spectrum, being discretized using 30 frequencies exponentially spaced with an increment of 10 %, $\Delta f = 1.1f$ and 24 directions ($\Delta \theta = 15^\circ$). For consistency with the frequency range retained in the phase-resolving simulations and observational processing, only the first 19 frequency bins were considered, corresponding to the interval 0.0345–0.2 Hz.

It should be noted that, although a higher spectral resolution could be implemented in WW3 at moderate computational cost, the present configuration is intentionally kept consistent with the operational MFWAM–WW3 system in order to evaluate the impact against forcing originating from typical operational spectral model configuration. In addition, as for any numerical model, errors can be significant. In the present case, the WW3 confrontation with T2-6 buoy data shows satisfactory agreement



for integral parameters (Fig. 2), with a coefficient correlation of 0.98, a bias of 7 cm, a root mean square deviation (RMSD) of 0.23 m and normalised RMSD of 12.7 % for significant wave height.

4.3.4 Trigonometric series

The wave spectrum provides an energy spectral density $E_{i,j}$, for a discrete set of frequencies f_i and directions θ_j of resolution Δf_i and $\Delta \theta$. The amplitude associated with each spectral element is:

$$a_{i,j} = \sqrt{2 \Delta f_i \Delta \theta E_{i,j}} \quad (12)$$

where $\omega_i = 2\pi f_i$ is the angular frequency.

To reduce persistent interference between discrete directional components sharing the same nominal frequency, a frequency-enrichment procedure is applied to both forcing sources. This method is based on the procedure proposed by Salatin et al. (2021), to which we suggest adjustments to avoid side effects on the IG band, whilst endeavouring to preserve the shape of the initial wave spectrum. Each spectral element above a prescribed cut-off frequency is replaced by four nearby frequency subcomponents. The reconstructed free-surface elevation is written as:

$$\eta(x, y, t) = \sum_i \sum_j \sum_{m=1}^{N_{s,i}} \frac{a_{i,j}}{\sqrt{N_{s,i}}} \cos[(\omega_i + \epsilon_{i,j,m})t + \phi_{i,j}(x, y) + \psi_{i,j,m}], \quad (13)$$

where $N_{s,i} = 4$ for $f_i \geq f_{\text{cut}}$ and $N_{s,i} = 1$ otherwise. The terms $\psi_{i,j,m}$ are fixed phase offsets assigned to the subcomponents.

For $f_i \geq f_{\text{cut}}$, two independent positive frequency offsets are generated for each frequency–direction pair:

$$\begin{cases} \delta f_{i,j}^{\text{in}} = b_i (0.15 + 0.25 U_{i,j}^{\text{in}}), \\ \delta f_{i,j}^{\text{out}} = b_i (0.60 + 0.35 U_{i,j}^{\text{out}}), \\ b_i = \min(0.40 \Delta f_i^{\text{eff}}, 1.5 \times 10^{-3} \text{ Hz}), \end{cases} \quad (14a)$$

$$\delta f_{i,j}^{\text{out}} = b_i (0.60 + 0.35 U_{i,j}^{\text{out}}), \quad (14b)$$

$$b_i = \min(0.40 \Delta f_i^{\text{eff}}, 1.5 \times 10^{-3} \text{ Hz}), \quad (14c)$$

where $U_{i,j}^{\text{in}}$ and $U_{i,j}^{\text{out}}$ are independent random variables uniformly distributed over $[0, 1]$, and Δf_i^{eff} is defined as the smaller of the two adjacent frequency spacings.

The four angular-frequency perturbations are then:

$$(\epsilon_{i,j,1}, \epsilon_{i,j,2}, \epsilon_{i,j,3}, \epsilon_{i,j,4}) = 2\pi (-\delta f_{i,j}^{\text{out}}, -\delta f_{i,j}^{\text{in}}, +\delta f_{i,j}^{\text{in}}, +\delta f_{i,j}^{\text{out}}). \quad (15)$$

The perturbations therefore form two independent symmetric pairs whose mean is zero so as not to introduce a frequency bias (since only a finite number of random realizations is used, the sample mean can deviate slightly from zero without taking this precaution), and no subcomponent remains at the nominal frequency above the cut-off. All random frequency and phase values are generated once at model initialisation and remain constant throughout the simulation. They also vary between frequency–direction pairs, thereby reducing persistent coherent superposition between directional components.

No frequency subdivision or perturbation is applied below $f_{\text{cut}} = 0.05$ Hz. For $f_i < f_{\text{cut}}$, Eq. (13) therefore reduces to a single component with $N_{s,i} = 1$, $\epsilon_{i,j,1} = 0$ and $\psi_{i,j,1} = 0$. This prevents the frequency-enrichment procedure from directly introducing additional modulation in the IG range.



The division of each component amplitude by $\sqrt{N_{s,i}}$ ensures that the sum of the squared subcomponent amplitudes is equal to the squared amplitude of the original spectral component:

$$\sum_{m=1}^{N_{s,i}} \left(\frac{a_{i,j}}{\sqrt{N_{s,i}}} \right)^2 = a_{i,j}^2 \quad (16)$$

The prescribed variance is therefore conserved at the level of each spectral element. Over finite-duration analysis windows, however, cross terms between phase-resolving subcomponents do not necessarily cancel completely, and the variance estimated from the reconstructed time series can consequently differ from the target spectral variance.

The spatial phase $\phi_{i,j}$ satisfies:

$$\begin{cases} \frac{\partial \phi_{i,j}}{\partial x} = k_i \cos(\theta_j) \\ \frac{\partial \phi_{i,j}}{\partial y} = k_i \sin(\theta_j) \end{cases} \quad (17a)$$

$$(17b)$$

where x and y are the horizontal orthogonal coordinates and k_i is the wave number associated with the nominal angular frequency ω_i . If k_i were independent of position, the spatial phase would be

$$\phi_{i,j}(x, y) = k_i \cos(\theta_j)x + k_i \sin(\theta_j)y + \phi_{i,j}^0 \quad (18)$$

In the present shallow-water configuration, however, the wave number depends on the local mean water depth $H(x, y)$ through the linear dispersion relation $\omega_i^2 = gk_i \tanh[k_i H(x, y)]$.

The spatial phase is therefore determined by integrating the right-hand sides of Eqs. (17a) and (17b) over the model grid. The velocity and non-hydrostatic pressure components are derived from the corresponding free-surface components using linear wave theory (Kinsman, 1965).

Last, WW3 provides no information on the phase, i.e. the above-mentioned uncertainty on the initial phase remains unchanged. In the absence of sufficient information, the initial phases $\phi_{i,j}^0$ and the subcomponent phase offsets $\psi_{i,j,m}$ must therefore be assigned algorithmically and are kept constant throughout each simulation. The resulting time series represents one possible phase realisation of the prescribed directional spectrum rather than the unique physical wave sequence that occurred in the field.

This simplified approach is questionable because real sea states may comprise several coexisting and temporally evolving wave systems—such as a locally generated wind sea and one or more swell systems originating from distinct source regions—which occupy separate partitions of the directional spectrum and whose phase relationships may evolve independently (Portilla et al., 2009). Such information cannot be recovered from a phase-averaged spectrum. However, this limitation is inherent to the use of phase-averaged spectral models and not specific to the present configuration. A more rigorous approach would consist in performing an ensemble of simulations with different random phase realizations and analyzing the resulting statistics (e.g., mean and extremes), although this would come at a substantially increased computational cost given that the spectral reconstruction in Eq. (13) can already involve more than a thousand spectral components if several dozen frequencies and directions are taken into account.

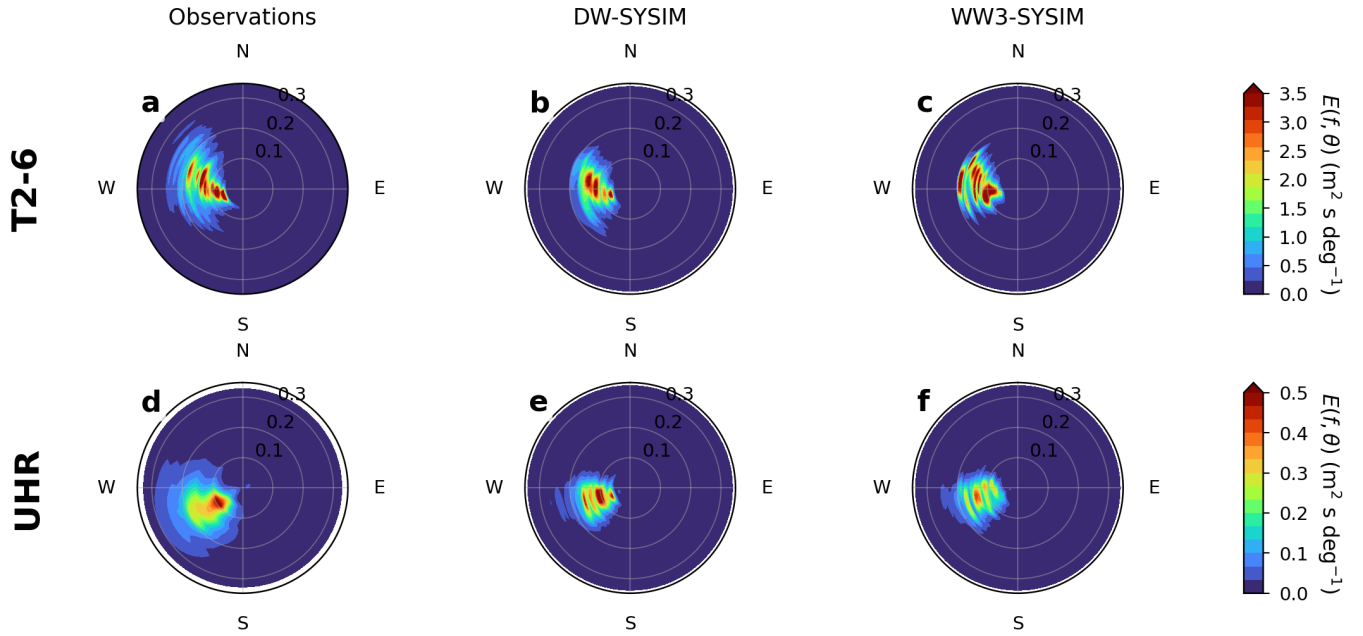


Figure 4. Observed (left column) and simulated directional spectra at T2-6 (a, b and c) and UHR (d, e and f) moorings on 14 January 2021 at 17:40 UTC. The middle column shows the results for the DW-SYSIM and the right column for the WW3-SYSIM.

5 Results

400 5.1 General patterns

Two model configurations are compared in this paper, one forced by the T2-6 Datawell wave spectra (DW-SYSIM simulation), one by WaveWatch III (WW3) spectra (WW3-SYSIM simulation). DW-SYSIM prescribes the directional spectrum measured at T2-6 uniformly along the western open boundary. WW3-SYSIM instead uses spatially varying WW3 directional spectra along the western, northern and southern open boundaries. These two simulations are hereinafter referred to as the reference
 405 simulations.

Comparison of directional wave spectra at the T2-6 mooring location (western offshore boundary of the phase-resolving model) during peak wave events in LEG3 ($H_{m0} = 2.7$ m; $T_p = 10$ s) measured at T2-6 on 14 January at 17:40 UTC) reveals that both simulations reproduce the dominant wave direction and the main directional spreading observed in the measurements (Fig. 4). The simulated spectra are generally consistent with the observations, although the directional distribution appears
 410 slightly narrower than measured. Differences between DW-SYSIM and WW3-SYSIM remain limited at this offshore location, suggesting that both boundary-forcing strategies provide a realistic description of the incoming wave field during this event.

At the intertidal UHR station, the simulations reproduce the dominant wave direction and its rotation towards an approximately shore-normal orientation due to refraction over the shallow platform. However, the observed spectrum is substantially broader in both frequency and direction. In particular, the measurements contain appreciable energy between 0.2 and 0.3 Hz,



415 whereas this high-frequency energy is strongly underestimated by both simulations. In shallow water, non-linear wave transformation, such as triad interactions, transfer energy from the spectral peak towards higher-frequency harmonics. Owing to their shorter wavelengths, these high-frequency components are resolved by fewer grid cells and may therefore be insufficiently resolved and more strongly affected by numerical dissipation.

420 Additional comparisons at selected locations within the domain (Fig. 5) show that the two simulations remain broadly consistent at the southern and eastern extraction points, where wave refraction progressively reshapes the wave field during propagation toward the shoreline. In contrast, near the northern boundary (at SPEC2 and BALEINES locations), the difference is striking, with large directional spreading toward the north observed for WW3-SYSIM and a much west-focused wave direction for DW-SYSIM. These contrasting spectral characteristics affect both the significant wave height distribution and the
 425 instantaneous wave-induced free-surface elevation anomalies snapshots shown in Fig. 6.

Offshore, WW3-SYSIM produces systematically higher significant wave heights in the west-southwest sector of the domain (Fig. 6). This enhancement is consistent with the combined influence of the slightly larger offshore wave heights supplied by WW3 during LEG3 and the additional wave components entering through the lateral boundaries. In fact, WW3 tends to overestimate H_{m0} during the LEG3 period, as evidenced by the comparison with observations in Fig. 2. Despite these discrepancies
 430 in the deep part of the domain, nearshore wave conditions remain comparable over the fully exposed western coastline. Both simulations reproduce the observed west-to-east decay of wave energy and yield similar significant wave heights in the immediate coastal zone. However, WW3-SYSIM additionally predicts a secondary wave system approaching from the northwest near the Baleines lighthouse, generating a typical crossed-sea state (Figs. 1 and 6). This feature cannot be accurately captured by DW-SYSIM, in which a single directional spectrum measured at the western offshore buoy is uniformly prescribed along
 435 the western boundary, whereas WW3-SYSIM uses spatially varying WW3 spectra along all the open boundaries.

Beyond differences in bulk wave parameters, both simulations exhibit pronounced wave-convergence zones extending over several hundred metres across the domain, with particularly strong signatures above the small submarine gullies. Offshore, where bathymetric refraction remains relatively weak, these patterns are mainly related to interference between discrete spectral
 440 components with closely spaced frequencies. The superposition of such components produces beat patterns, characterised by alternating zones of enhanced and reduced wave energy and, consequently, by spatial modulations of significant wave height. These artificial patterns were substantially reduced by applying the frequency de-coherence procedure proposed by Salatin et al. (2021) with the additional modifications described in Section 4.3.4. However, when the incident spectrum is represented by a limited number of discrete frequency-direction components, residual interference patterns remain: components may retain
 445 excessive phase coherence and generate spatially persistent beat patterns. Because the WW3 spectrum has a coarser frequency and directional discretisation than the Datawell spectrum, fewer independent components represent the incident sea state and more persistent interference patterns may remain in WW3-SYSIM simulation, even after de-coherence.

In the nearshore zone, wave-convergence and focusing patterns are more localized, showing a significant alongshore variability over scales of dozens/hundreds of meters. Additional tests have been carried out using a smoothed bathymetry in order



450 to discriminate the role of topography-driven focalisation effects in the development of such wave height modulation patterns. The smoothed bathymetry was obtained by applying 10,000 iterations of an explicit iterative Laplacian filter to the original dataset. The resulting bathymetry preserves the large-scale morphology of the shoreface while strongly reducing bathymetric variability at scales of a few tens of metres and largely removing structures with characteristic scales of the order of 100 m and below. The bottom-friction coefficient was kept unchanged between the two simulations, so that the comparison isolates
 455 the effect of bathymetric smoothing rather than changes in dissipation parameterisation. Figure 7 illustrates the predominant observation for a representative zoomed view for the area surrounding transects T2 and T3. With the original bathymetry, the significant wave height field displays a pronounced spatial imprint of small-scale seabed features, with alternating zones of enhanced and reduced wave energy. Local depth variations modify phase and group velocities, causing refraction and spatial convergence or divergence of wave energy, and therefore localized focusing and defocusing. Abrupt bathymetric gradients may
 460 additionally induce wave scattering or partial reflection, which could contribute to interference patterns, although the relative importance of these processes cannot be established from the present diagnostics alone. The smoothed bathymetry leads to a substantially smoother significant wave height field, characterized by a strong attenuation of the alongshore variability. Both simulations nevertheless reproduce qualitatively similar large-scale significant wave height patterns and remain broadly consistent with the in situ observations shown in Fig. 7. This observation highlights the sensitivity of phase-resolving simulations
 465 to the representation of small-scale bathymetric variability. However, it does not establish whether all the fine-scale structures obtained with the original bathymetry are physical, since they may also be influenced by bathymetric uncertainty, grid resolution, or numerical treatment of steep depth gradients. Consequently, this comparison should be interpreted as an assessment of the variability associated with bathymetric representation rather than as evidence of the superiority of either simulation. A more quantitative assessment of model performance is provided in the section 5.3.

470 5.2 Effectiveness of boundary conditions at open borders

Particular attention is paid to verifying that incoming waves propagate through the domain consistently with their prescribed forcing, especially because outgoing waves near the lateral boundary are diagnosed from the difference between the total SSH field (that calculated by the model) and the incoming field (given by the definition of forcing). In other words, the outgoing signal is correctly identified only if the incoming field is very close to its definition in the forcing. This is not self-evident, as the
 475 boundary condition scheme must simultaneously satisfy both outgoing and incoming properties, and so needs to be verified.

A third simulation called `WW3WEST-SYSIM` is thus implemented, forced by WW3 spectra only at the West and South boundaries. This simulation will be compared with the simulation where WW3 forcing enters through all the domain's lateral boundaries. In the vicinity of the northern border of the `WW3WEST-SYSIM` simulation, waves are only outgoing. Phase velocity diagnostics cannot be interfered with by incoming waves, so the phase velocity is unambiguously that of outgoing waves.

480 When looking at instantaneous phase velocity and its Exponential Moving Average (EMA)-filtered counterpart, obtained from `WW3WEST-SYSIM` simulation (Fig. 8a), that is without incoming waves along the northern open boundary, the unreliability of the instantaneous phase velocity is highlighted, which exhibits spurious extrema due to division by near-zero values during its computation. Meanwhile, Fig. 8d demonstrates the consistency between the black line slope (given by phase veloci-

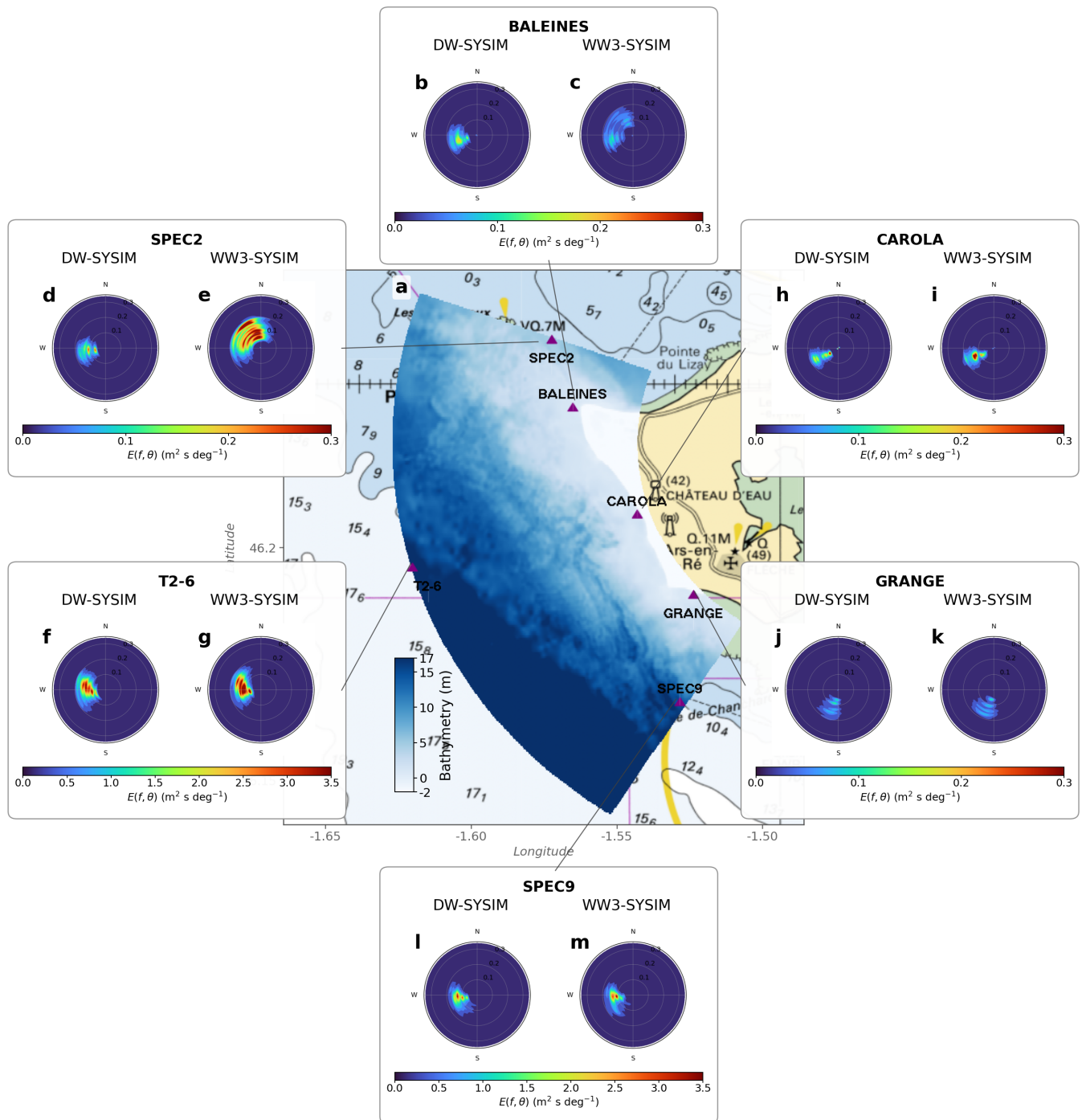


Figure 5. Bathymetry (a) and directional spectra (b to m) near the boundaries and nearshore with the DW-SYSIM (b, d, f, h, j, l) and WW3-SYSIM (c, e, g, i, k and m) simulations on 14 January 2021 at 17:40 UTC.

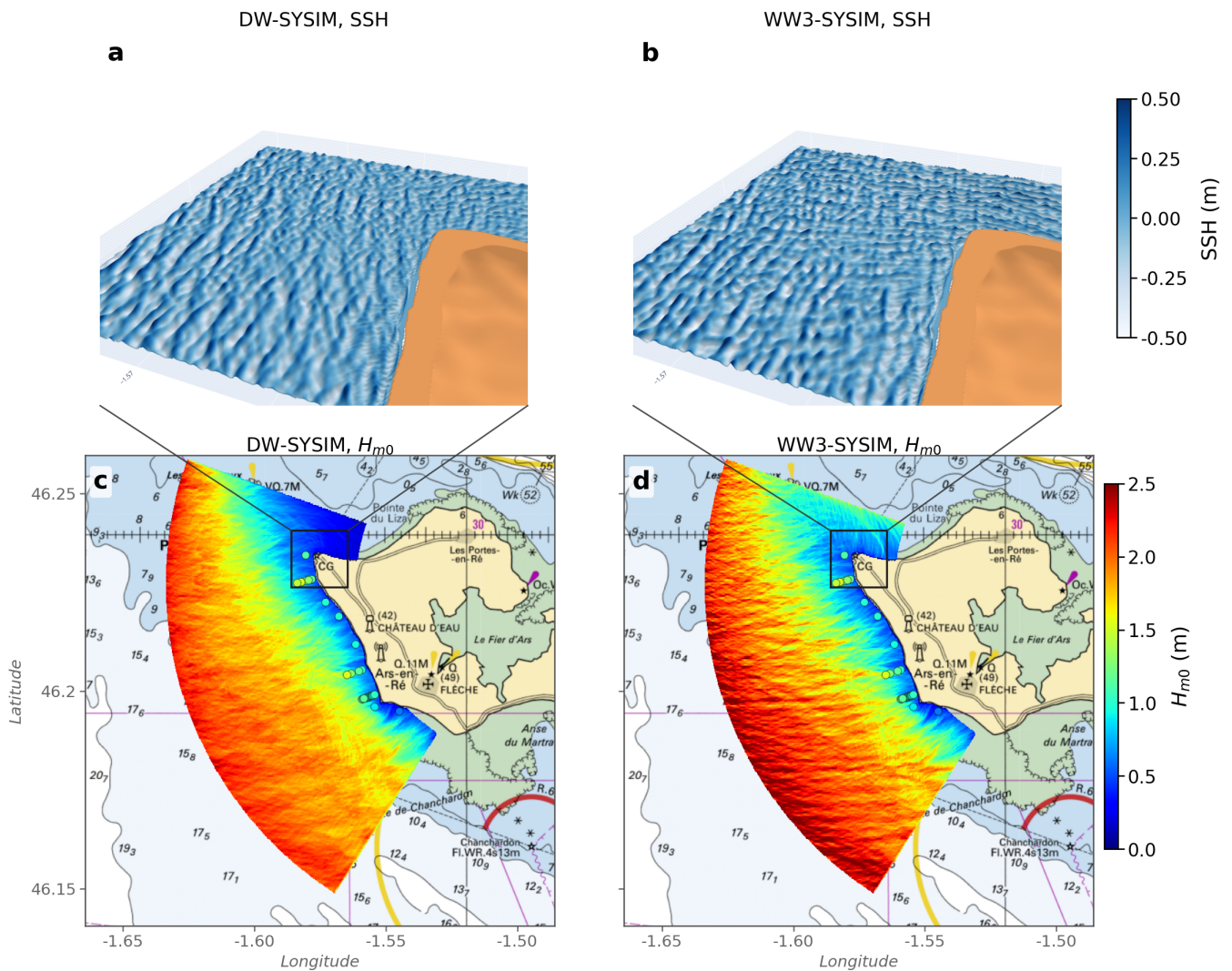


Figure 6. Wave-induced sea-surface elevation anomaly map, obtained after removing the low-frequency sea surface height (SSH) field (a and b) at the Baleines lighthouse area and H_{m0} maps (c and d) for the entire simulated domain on 14 January at 17:30 UTC, for the DW-SYSIM simulation (a and c) and the WW3-SYSIM simulation (b and d). In circle the H_s value measured at the instruments.

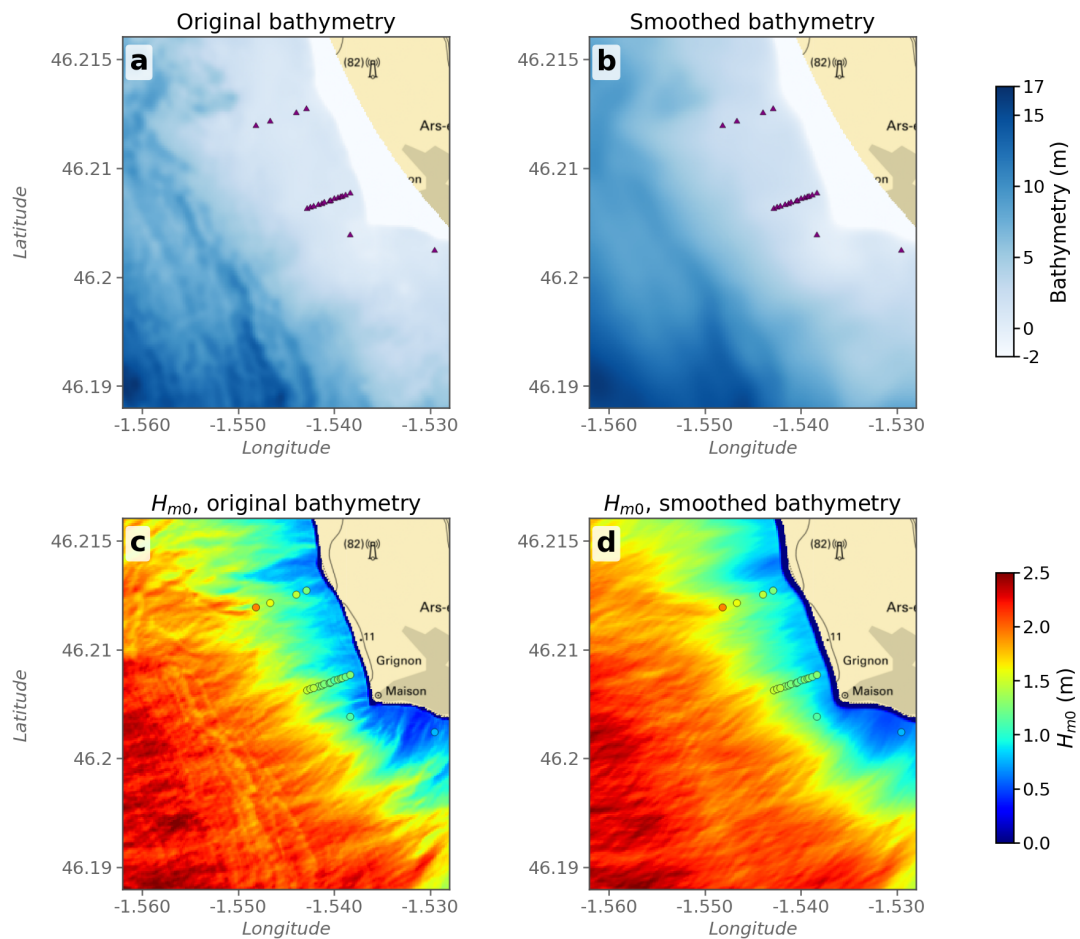


Figure 7. Original bathymetry used by both DW-SYSIM and WW3-SYSIM simulations (a) and a smoothed version (b) for the area surrounding transects T2 and T3. In triangle, the location of the instruments. H_{m0} maps on 14 January at 17:30 UTC, for the DW-SYSIM simulations (c) and for the same simulation on the smoothed bathymetry (d). In the circle, the H_s value measured at the instruments.



ties diagnosed by the EMA method) and the slope of the SSH isocontours, thereby validating the accuracy of the EMA-filtered
 485 phase velocity diagnostic (indeed slopes must be the same near the boundary if the phase velocity is correctly estimated).

In the WW3WEST-SYSIM simulation, calculating the speed of outgoing waves involves first separating outgoing and incoming waves. The outgoing waves are given by the difference between the total signal and the incoming waves. It is therefore assumed that the incoming waves are faithful to the definition of the forcing, but this is only true if the incoming boundary condition properties work correctly.

490 Comparison of the outgoing EMA-filtered phase velocities of (WW3-SYSIM) and (WW3WEST-SYSIM) (Fig. 8b) shows that the phase velocity remains nearly identical in both configurations, confirming that the method correctly distinguishes between incoming and outgoing wave components. Since the outgoing component is identical in both simulations, the resulting phase velocity should also be consistent — which is observed.

The estimate of the phase velocity of outgoing waves is similar whether or not the total field is mixed with an incoming field,
 495 because the estimate of the outgoing SSH in the general situation (mixed with incoming waves) is similar to the SSH in the situation without waves entering from the north (Fig. 8c), even when incoming SSH signal is not negligible (i.e. Fig. 8c, where the black curve of incoming waves represents a significant proportion of the total signal). This demonstrates the robustness of the method under realistic conditions.

Besides, outgoing waves are therefore correctly identified only if incoming waves propagate in accordance with the forcing
 500 definition. To preserve this property, care must be taken to ensure that the forcing spectrum contains only wavelengths compatible with the grid horizontal resolution, which means restricting the number of WW3 frequencies taken into account (only the first 19 frequencies are used, up to 0.2 Hz) to keep only wavelengths greater than or equal to the model effective resolution.

5.3 On the foreshore

The two reference simulations DW-SYSIM and WW3-SYSIM are compared with measurements on the foreshore during LEG3.
 505 Comparisons are presented for the H_{m0} integrated wave parameter on the gravity band, as well as for the frequency spectra.

5.3.1 Significant wave height

We focus here on Transect 3 (T3) located in the southern part of the study area, which is representative of the model performance while covering the most instrumented cross-shore section. Detailed time series for Transects 1 and 2 (T1, T2) are provided in Appendix B (Figs. B1–B3). Table 1 summarizes the bias (BIAS), the coefficient of determination (R^2), and Will-
 510 mott index (WI) across all transects and sensors during the LEG3 period.

Figure 9 depicts the H_{m0} time series along T3, during the January acquisition week. The results are depicted for a subset of sensors, from PT2 to G12 located at the offshore and onshore limits of T3, respectively (see Fig. 1). The Miche criterion, defined as $\gamma = \frac{H_{m0}}{\sqrt{2}H}$ and calculated with the observations, is also included to identify breaking conditions.

Overall, the implementation of the wetting and drying scheme enables a realistic representation of tidally-driven foreshore
 515 exposure, with both simulations reproducing the temporal evolution of H_{m0} with good agreement against the observations along the different transects (Fig. 9 and Table 1). During the first tidal cycles, the Miche criterion exhibits a parabolic shape,

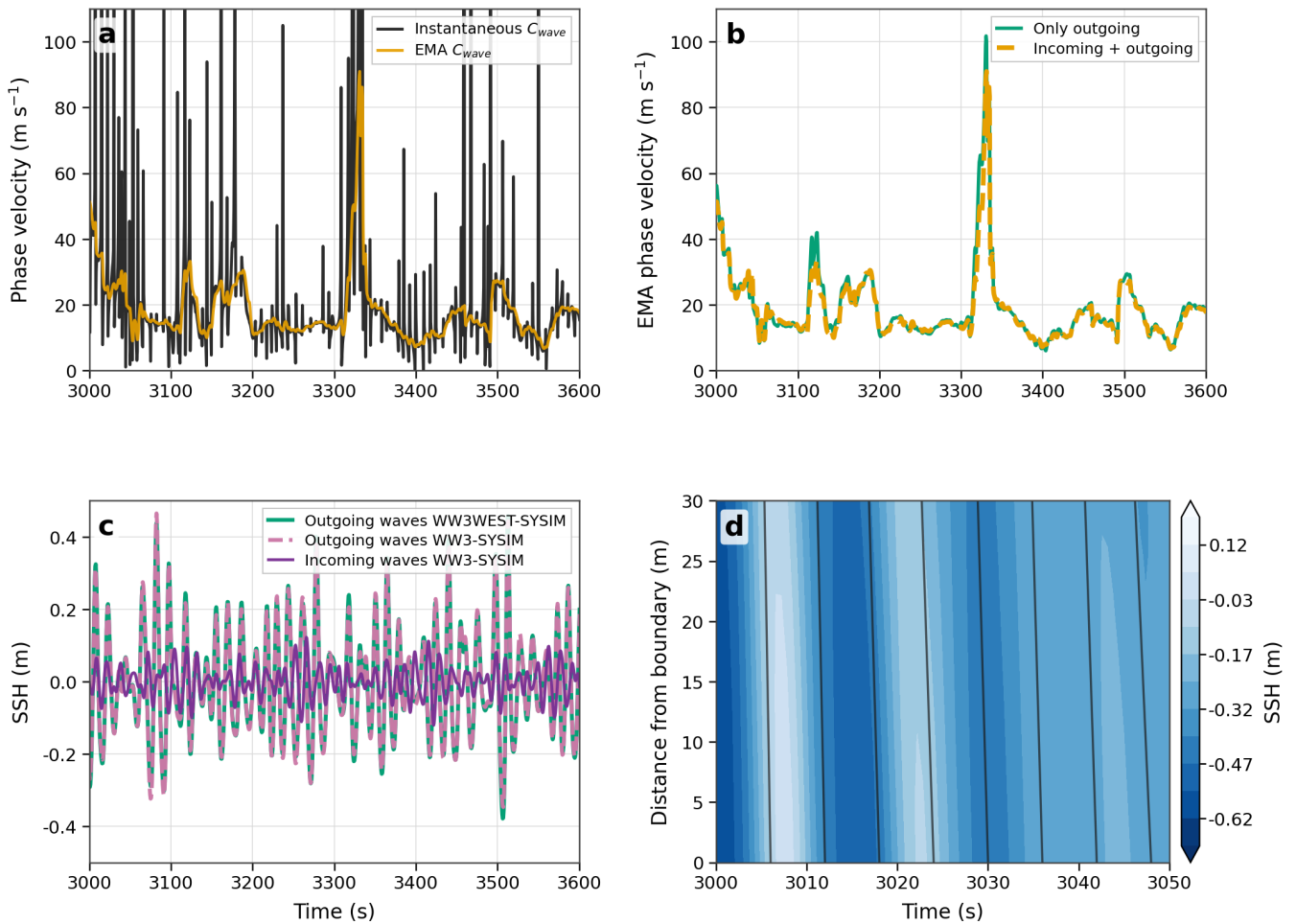


Figure 8. Time series at the north boundary (j=41) on 11th January at 10:15 UTC for a: Instantaneous phase velocity and phase velocity filtered by EMA at the north boundary for the WW3WEST-SYSIM simulation, b: Phase velocities filtered by EMA at the north boundary for the WW3WEST-SYSIM (that simulate only outgoing waves) and the WW3-SYSIM simulations (that simulate incoming and outgoing waves), c: SSH at the north boundary for the incoming and outgoing waves of WW3-SYSIM and for the outgoing waves of WW3-SYSIM and WW3WEST-SYSIM, d: Hovmöller diagram at the same point for the WW3WEST-SYSIM simulation. In black, the lines with a slope equal to the phase velocity filtered by EMA. The slope of the isolines, quite regular and always negative near the boundary condition at $x=0$, shows the absence of spurious reflected waves



indicating predominantly non-breaking conditions. Over these periods, both DW-SYSIM and WW3-SYSIM closely follow the observed wave height variability at all sensors. Under breaking-wave conditions (i.e., when the Miche criterion reaches a nearly saturated value), slight discrepancies emerge, particularly at the onshore sensors where wave heights tend to be underestimated during peak conditions. This behaviour is especially visible also at the G12 location, where both simulations underestimate the observed wave heights during high tide conditions. Despite these discrepancies, the statistical metrics remain high at most transect sensors (Table 1). Biases remain limited at most T2 and T3 sensors, while larger systematic underestimations occur along parts of T1, at BALEINES and at some onshore T3 stations. Willmott indices are generally high, although lower values occur at several isolated nearshore stations.

The behaviour observed along T3 is representative of the general behaviour of the model, although significant spatial variability in model skill is observed across the study area (Figs. B1–B3; Table 1). The best agreement is obtained along T2, where both simulations reproduce the tidal modulation and temporal variability of H_{m0} with small biases and high Willmott indexes across most sensors. Slightly lower performances are obtained along T1 and for some nearshore sensors, where wave height maxima tend to be underestimated during energetic conditions. Sensitivity tests revealed that these discrepancies are strongly dependent on the choice of bottom friction coefficient. In particular, reducing the bottom friction from $C_d = 0.6 \text{ m}^{-1}$ to $C_d = 0.4 \text{ m}^{-1}$ (Fig. B1) substantially improves the agreement along T1. This behaviour highlights the strong sensitivity of nearshore wave transformation to dissipation parameterisations in shallow environments and suggests that a single uniform bottom friction coefficient may not optimally represent the spatial variability of seabed roughness and dissipative processes across the entire study area.

The WW3-SYSIM simulation, forced with offshore spectra on all boundaries, yields results that are generally consistent with those obtained using DW-SYSIM. Across the different transects, both configurations reproduce similar temporal patterns and tidal modulation of H_{m0} , with comparable statistical performances. Nevertheless, localized differences emerge depending on the wave conditions and sensor locations. Along T1, WW3-SYSIM tends to produce lower wave heights during energetic conditions, leading to a moderate degradation of the statistical metrics at some sensors. Conversely, both simulations remain very close over T2 and T3, where the agreement with observations is excellent (except for onshore stations of T3). These differences highlight the sensitivity of nearshore wave transformation to the offshore spectral forcing and associated dissipation processes. However, the overall consistency between DW-SYSIM and WW3-SYSIM demonstrates that the modelling framework remains robust under different offshore forcings, with both configurations showing a similar capability to reproduce the temporal variability of wave heights across the surveyed area.

Overall, both DW-SYSIM and WW3-SYSIM demonstrate robust performance over the surveyed area, despite localized differences in the reproduction of significant wave height maxima. The spatial variability in model skill likely results from several sources of uncertainty. First, wave breaking and bottom friction are represented using simplified parameterisations that may not fully capture the spatial and temporal variability of dissipative processes associated with local hydrodynamics and seabed roughness. Although the bathymetry is derived from high-resolution multibeam and LiDAR surveys and is therefore considered highly accurate, its numerical representation may still affect the simulations through grid interpolation, the smoothing required for model stability, and the unresolved influence of small-scale seabed features. The strong sensitivity of the modeled



555 wave field to bathymetric smoothing, highlighted previously, reflects the importance of these representation choices rather than a limitation of the bathymetric dataset itself. Uncertainties in the offshore wave forcing may also locally affect the simulated wave transformation. Finally, partial wave reflection at the beachface may also induce complex spatial modulations of the wave field, affecting the comparison with the observations. However, the available measurements do not allow quantification of reflection processes in such a strongly three-dimensional environment.

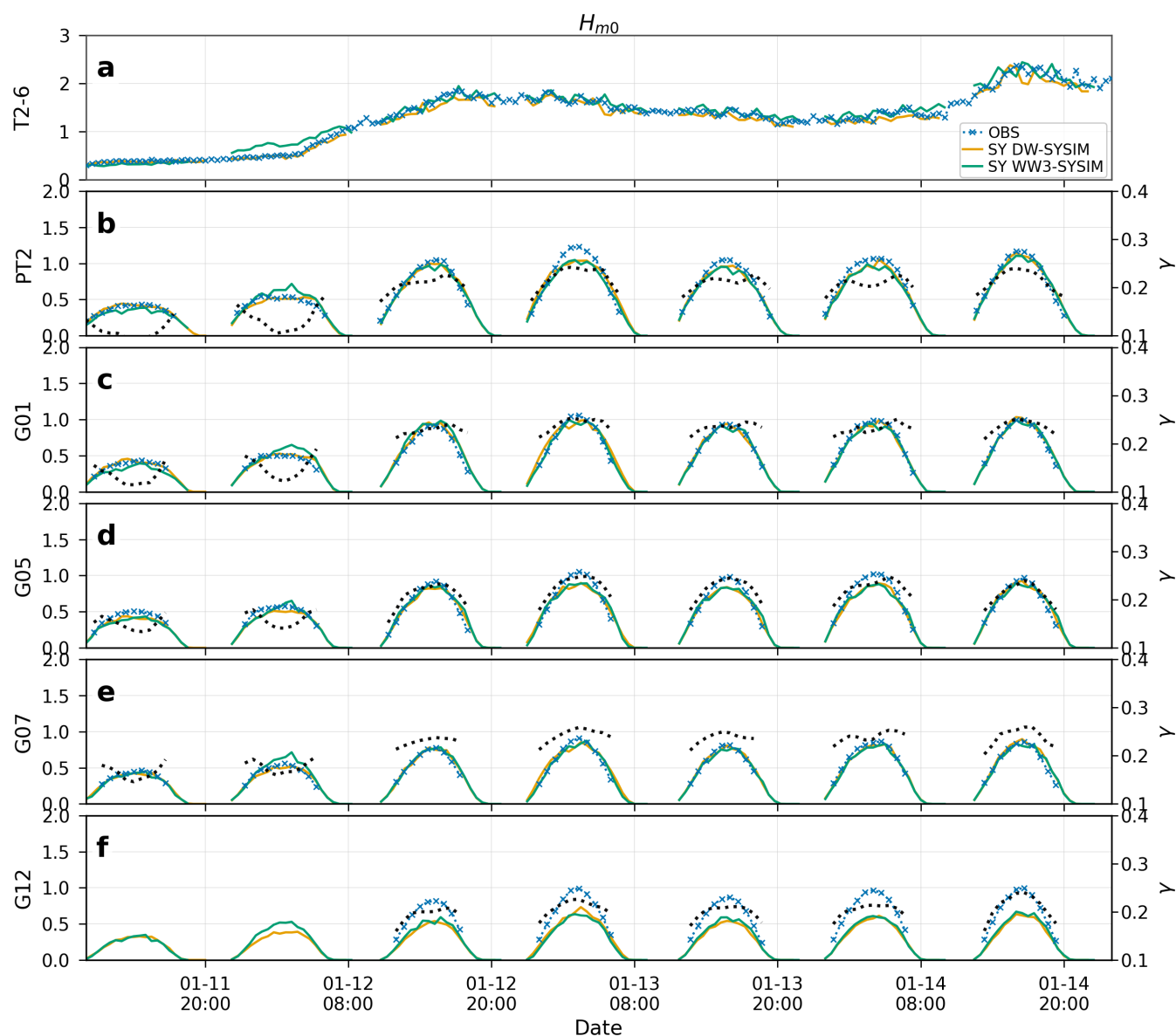


Figure 9. Simulated and observed H_{m0} time series during LEG3 in several instruments from offshore (T2-6, a) to the Transect 3 (b: PT2, c: G01, d: G05, e: G07 and f: G12). In blue are the observations, in orange the DW-SYSIM simulation, and in green the WW3-SYSIM simulation. On top are the simulated and measured values at T2-6, and below the values on Transect 3 from offshore to onshore. In black, the Miche criterion calculated with the observations.



Transect	Sensor	DW-SYSIM			WW3-SYSIM		
		BIAS	R^2	WI	BIAS	R^2	WI
T1	T1-1	-0.20	0.95	0.71	-0.21	0.90	0.69
	T1-2	-0.17	0.91	0.76	-0.22	0.79	0.67
	T1-2BIS	-0.20	0.95	0.70	-0.21	0.83	0.68
	T1-3	-0.20	0.94	0.77	-0.26	0.86	0.69
	T1-4	-0.14	0.92	0.84	-0.23	0.90	0.71
T2	T2-1	-0.07	0.93	0.91	-0.09	0.94	0.93
	T2-2	-0.04	0.95	0.95	-0.06	0.93	0.96
	T2-3	0.05	0.96	0.97	0.07	0.89	0.95
	T2-4	0.01	0.90	0.96	0.00	0.90	0.97
	T2-5	0.00	0.95	0.98	0.12	0.92	0.96
T3	G12	-0.24	0.91	0.73	-0.23	0.92	0.74
	G11	-0.15	0.92	0.84	-0.14	0.92	0.85
	G10	-0.18	0.91	0.81	-0.17	0.91	0.83
	G09	-0.13	0.92	0.87	-0.12	0.92	0.89
	G08	-0.11	0.91	0.89	-0.11	0.92	0.90
	G07	0.00	0.92	0.98	0.00	0.91	0.97
	G06	-0.04	0.92	0.97	-0.03	0.91	0.96
	G05	-0.05	0.93	0.97	-0.04	0.89	0.96
	G03	0.01	0.91	0.97	0.02	0.90	0.97
	G02	0.00	0.93	0.98	0.01	0.91	0.98
	G01	0.01	0.95	0.99	0.00	0.93	0.98
	PT4	-0.05	0.95	0.98	-0.06	0.94	0.97
	PT3	-0.03	0.95	0.98	-0.04	0.94	0.98
	PT2	-0.03	0.95	0.98	-0.04	0.94	0.98
nearshore	BALEINES	-0.24	0.95	0.66	-0.21	0.92	0.71
	CAROLA	-0.05	0.69	0.85	-0.10	0.78	0.77
	GRANGE	0.00	0.83	0.94	-0.01	0.80	0.94
	GRIGNON	0.06	0.89	0.94	0.04	0.84	0.94
	GRIVEAU	-0.14	0.92	0.75	-0.13	0.92	0.78
	OURS	-0.10	0.92	0.87	-0.13	0.92	0.79

Table 1. Statistical H_{m0} scores (bias (BIAS), coefficient of determination (R^2), and Willmott index (WI)) for sensors of each transect for the two simulations DW-SYSIM and WW3-SYSIM. Font styles provide a qualitative indication of model performance: bold, regular, and italic values indicate good, intermediate, and poor performance, respectively. For the absolute bias, these categories correspond to $|\text{BIAS}| \leq 0.10$ m, $0.10 < |\text{BIAS}| \leq 0.20$ m, and $|\text{BIAS}| > 0.20$ m, respectively. For R^2 and WI, they correspond to scores ≥ 0.90 , between 0.70 and 0.90, and < 0.70 , respectively.



5.3.2 Frequency spectra

Additional insight into the wave transformation processes is provided by the comparison of measured and simulated frequency spectra at selected offshore and nearshore locations along T3. Figure 10 presents the temporal evolution of the frequency spectra at PT2 and G07, while Fig. 11 shows corresponding one-dimensional spectra for two representative periods during moderately and high-energetic conditions.

Both DW-SYSIM and WW3-SYSIM successfully reproduce the dominant spectral peak and the overall temporal evolution of the spectral energy distribution up to approximately 0.2 Hz. The main wave components and their modulation during the tidal cycles are consistently captured at both offshore (PT2) and nearshore (G07) locations. The two simulations also reproduce the broadening of the spectral energy observed during energetic conditions. Differences between the simulations remain mostly confined to the detailed distribution of energy around the peak, the IG band and the high-frequency tail.

During the lower-energy period on 12 January (Fig. 11a, c), both simulations reproduce the dominant peak reasonably well. WW3-SYSIM generally produces a broader sea-swell spectrum and locally higher energy around the peak than DW-SYSIM. In the IG band, WW3-SYSIM is in relative good agreement with the observations, whereas DW-SYSIM underestimates them. During the more energetic period on 14 January (Fig. 11b, d), agreement improves in the main sea-swell band, with both simulations reproducing the observed peak frequency and magnitude. Both simulations underestimate largely the observed IG energy at PT2 and G07 for this period, although WW3-SYSIM generally retains more IG energy than DW-SYSIM.

Above approximately 0.2 Hz, the simulations underestimate the observed spectral energy and produce narrower high-frequency tails. This behaviour is consistent with the finite grid resolution and numerical dissipation of the phase-resolving model, which limit the representation of the shortest resolved waves and of energy transfers towards higher harmonics.

Preliminary sensitivity tests in the frequency de-coherence procedure, showed that perturbing the frequencies below approximately 0.05 Hz, create artificial low-frequency modulation at the open boundaries. With the actual implementation of the procedure in the reference simulations, the random frequency offsets are drawn once at initialization and are not applied below 0.05 Hz, and thus no substantial additional energy in the IG band is generated (Fig. C1).

Complementary simulations with reduced or disabled frequency perturbations produced moderate and non-monotonic changes in IG energy. However, the generally larger IG response obtained with WW3 forcing persisted, indicating that the difference between the two reference simulations cannot be attributed solely to the frequency de-coherence procedure (not shown).

Overall, both forcing configurations reproduce the dominant sea-swell transformation from offshore to nearshore. The remaining discrepancies are mainly concentrated in the IG range and above 0.2 Hz.

6 Discussion

This study aimed to evaluate the ability of a phase-resolving model to reproduce complex nearshore wave dynamics under realistic boundary forcing conditions, including tides, currents, and directional wave spectra, in a rocky coastal environment.

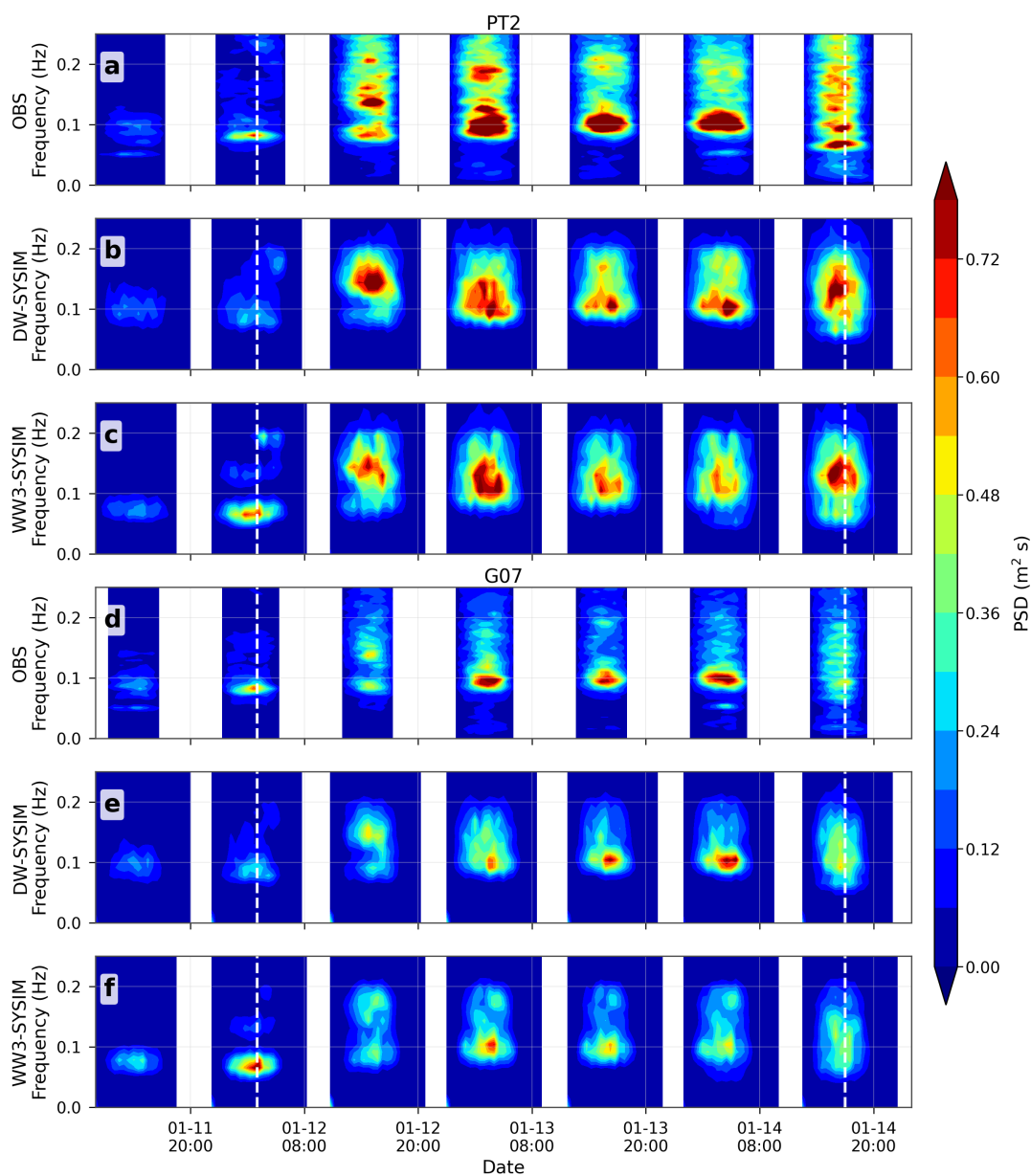


Figure 10. Observed spectra and simulated spectra for the simulations DW-SYSIM and WW3-SYSIM along transect 3, as a function of time and frequency, at PT2 (a, b and c) and G07 (d, e and f) during LEG3. The white vertical dashes indicate the dates of the 1D spectra shown in the Fig. 11

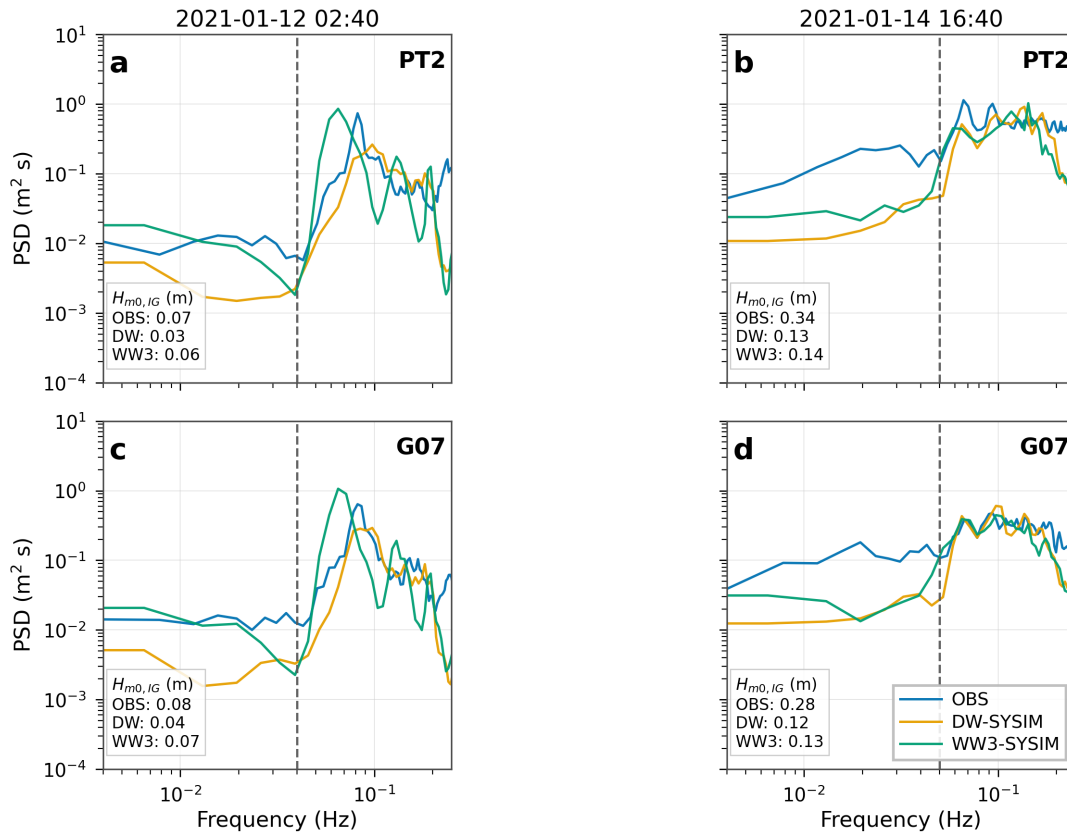


Figure 11. Observed and simulated frequency spectra at PT2 (top row) and G07 (bottom row) on 12 January at 02:40 UTC (left column) and 14 January at 16:40 UTC (right column). Observations are compared with DW-SYSIM and WW3-SYSIM. Grey dashed lines indicate the separation between the IG and sea-swell bands. The values reported in each panel indicate the corresponding IG significant wave height, $H_{m0,IG}$.

The primary objective was to assess whether using realistic, time-varying spectral forcings at the boundaries improves the representation of wave transformation, particularly in terms of spectral content in the nearshore zone.

While improvements in boundary forcing increase the realism of the model configuration, they do not automatically translate into improved performance across the entire domain. A key limitation arises from the absence of phase information in the wave forcing conditions: spectral models represent the distribution of energy across frequencies and directions but lack the phase of individual wave components, making it impossible to reconstruct time series that are fully consistent with measured conditions. This limitation constrains direct comparisons with instantaneous observations and affects the ability to capture extreme, phase-dependent events critical for coastal flooding and swash studies (Henderson et al., 2022). Besides, simulations were conducted over 30-minute windows to match the periods over which the measured spectra were computed. While enabling consistent spectral comparisons, such short windows may not capture the statistical variability of the sea state or rare extremes (Salatin et al., 2021; Treillou et al., 2024). This raises challenges for operational implementation, where capturing extremes is crucial



600 but computationally expensive. Alternative strategies, including data-driven approaches or machine learning emulators, could be developed to infer the occurrence and magnitude of rare events efficiently while limiting computational costs.

The study underscores the importance of local hydrodynamic features, bathymetric representation, and dissipation parameterisations for reliable nearshore wave modelling.

605 Significant spatial modulations of the wave field occur in the shoaling and surf zones and are strongly sensitive to the numerical representation of bathymetry. These patterns may combine physical refraction and focusing with scattering, partial reflection, interpolation effects and grid-scale numerical sensitivity. Additional simulations using a smoothed bathymetry demonstrated a strong reduction of alongshore variability, emphasizing the sensitivity of phase-resolving models to fine-scale seabed morphology. In the present study, the combination of high-resolution multibeam and LiDAR surveys provides a particularly detailed alti-bathymetric dataset. The remaining sensitivity therefore primarily concerns how these data are interpolated
610 onto the computational grid and modified by the smoothing required for numerical stability, rather than the accuracy of the surveys themselves. At the shoreline, such wave-focusing patterns may induce highly variable alongshore exposure to wave energy, potentially leading to localized hotspots of coastal hazard. These results stress the need to preserve relevant morphological scales when constructing model bathymetries, particularly in complex rocky nearshore environments and in sandy
615 environments subject to rapid morphological changes.

The calibration of bottom friction and wave breaking parameters has a significant influence on the model's ability to reproduce wave heights and spectral distributions, especially in the surf zone. Sensitivity tests showed that reducing the bottom friction coefficient from $C_d = 0.6 \text{ m}^{-1}$ to $C_d = 0.4 \text{ m}^{-1}$ substantially improves the agreement along T1 during energetic conditions, indicating that a single uniform friction parameter may not optimally represent the spatial variability of seabed
620 roughness and dissipative processes across the entire domain.

These results suggest that improving offshore forcing alone is insufficient to systematically improve nearshore wave predictions when the numerical representation of fine-scale bathymetric features and the parameterisation of dissipative processes remain controlling factors. Future work should therefore focus on site-specific calibration strategies informed by spatially resolved seabed-roughness metrics (Sous et al., 2024; Geindre et al., 2025). Ongoing studies are currently investigating how
625 seabed metrics can be directly related to wave energy dissipation (Dealbera et al., 2024), with new parameterisations of bottom friction over rocky bottoms being developed for phase-resolving models (Guélard Ancilotti et al., 2024). In parallel, efforts to improve wave-breaking parameterisations are underway, particularly regarding the representation of wave shape evolution in shoaling and surf zones, which strongly controls spectral transfers and high-harmonic generation.

630 In this study, we focused on a period during which the largest number of instruments was deployed at sea. However, this period was relatively low in energy and therefore not particularly favorable for investigating IG waves. The analysis of frequency spectra provides additional insight into the representation of low-frequency motions. The one-dimensional spectra indicate that both simulations reproduce the dominant sea-swell energy reasonably well, including the evolution of the main spectral peak from offshore to nearshore areas. Differences remain visible in the low-frequency band, particularly at nearshore locations.



635 However, these discrepancies are not systematic enough to conclude that the model fails to reproduce frequency spectra of
 IG waves. Instead, they suggest that low-frequency motions are only partly represented under the present configuration. At
 some locations, the observed low-frequency modulations may also represent partial wave reflection and interference patterns
 in the surf zone, which are difficult to assess quantitatively with the available measurements in such a highly three-dimensional
 environment.

640 The sensitivity experiments distinguish artificial low-frequency energy introduced during boundary reconstruction from IG
 waves generated within the phase-resolving domain. After excluding frequency perturbations below 0.05 Hz, the *WW3-SYSIM*
 simulation still generally produces more IG energy than the *DW-SYSIM* simulation. Frequency de-coherence therefore modu-
 lates the detailed response but does not appear to be its primary origin.

The residual difference may be associated with characteristics of the reconstructed incident sea-swell field that are not fully
 645 described by the energy spectrum. In particular, the coarser *WW3* frequency-direction grid concentrates energy into fewer
 components, while the random phase realization and the spatial distribution of forcing along the open boundaries may produce
 a different wave-group structure. Difference-frequency interactions acting during propagation and shoaling could consequently
 generate different bound-IG responses. This remains a working hypothesis, because no direct phase-coherence is available, and
 the simulations cover relatively short windows with a single phase realization.

650 The interpretation is further complicated by the coexistence of free and bound IG components. Although free IG waves may
 contribute to the low-frequency energy (Akrish et al., 2025; Ardhuin et al., 2014), previous studies in the Bay of Biscay suggest
 an important role for locally generated bound IG (Crawford et al., 2015; Bertin et al., 2020). The remaining discrepancies may
 therefore combine differences in incident wave-group structure with nearshore generation, reflection and dissipation. Longer
 simulations during energetic periods, ensembles of phase realizations and dedicated diagnostics of incident and reflected com-
 655 ponents would be required for a quantitative attribution.

7 Conclusion and perspectives

This study demonstrates the application of a phase-resolving, non-hydrostatic model forced with realistic, time-varying wave,
 tide, and current conditions to simulate complex nearshore wave dynamics in a rocky shoreface environment. Particular atten-
 tion is given to the treatment of open boundaries, notably the phase-resolving radiation of outgoing waves and the reconstruction
 660 of incoming wave fields from directional spectra, as well as to the influence of the bathymetric representation and dissipation
 parameterisations.

Two complementary forcing strategies were compared. In *DW-SYSIM*, the directional spectrum measured at the offshore
 buoy is prescribed uniformly along the western open boundary. In *WW3-SYSIM*, spatially varying *WW3* spectra are imposed
 along all three open boundaries. Neither strategy is uniformly superior: the buoy forcing benefits from the high frequency
 665 and directional resolution of a locally observed spectrum, whereas the *WW3* forcing accounts for the spatial variability of
 the incident wave field and for lateral wave contributions, but relies on a more coarsely discretised and modelled directional
 spectrum.



Both reference simulations reproduce the dominant sea-swell transformation and the temporal variability of significant wave height reasonably well over most of the instrumented transects. The remaining errors are spatially heterogeneous and increase at some nearshore stations, where the response becomes particularly sensitive to local bathymetric gradients, dissipation and unresolved seabed roughness. Both simulations also underestimate energy above approximately 0.2 Hz, which is consistent with the finite model resolution and numerical dissipation.

Because the phases of the spectral components are unknown, the incoming wave fields are reconstructed using four symmetrically shifted subcomponents with frequency and phase perturbations fixed throughout each simulation. Excluding perturbations below 0.05 Hz prevents the reconstruction procedure from directly introducing artificial IG energy at the boundaries. Sensitivity tests nevertheless show that, although this procedure influences the detailed IG response, the differences between DW-SYSIM and WW3-SYSIM simulations also depend on the incident spectral characteristics and their subsequent nearshore transformation.

The bathymetric sensitivity experiments further demonstrate that the simulated wave field is strongly affected by the numerical representation of local seabed morphology. Smoothing the computational bathymetry substantially reduces the alongshore variability of significant wave heights, confirming that small-scale depth gradients control part of the simulated focusing and defocusing zones. However, this result does not establish that all fine-scale structures obtained with the original bathymetry are physical, nor that the smoothed bathymetry is preferable. The response may combine physical refraction and focusing with scattering, partial reflection, interpolation effects and grid-scale numerical sensitivity. The smoothing experiment should therefore be interpreted as a measure of uncertainty associated with bathymetric representation rather than as evidence of insufficient survey accuracy.

Overall, the results show that phase-resolving nearshore simulations can reproduce the principal characteristics of wave transformation in a highly heterogeneous coastal environment, but that their local accuracy depends strongly on how the incident spectrum, seabed morphology and dissipation processes are represented. Future developments should therefore focus on carefully constructed computational bathymetries, spatially varying roughness and friction formulations, and improved characterisation of the directional and phase structure of the boundary forcing. Longer energetic simulations and ensembles of phase realizations will also be required to quantify the respective contributions of spectral discretisation, wave-group coherence and nearshore non-linear processes to IG wave generation.

Code availability. The source code of version 3.8.9 of Symphonie used in this work can be found at <https://doi.org/10.5281/zenodo.20527266> (Marsaleix et al., 2026) and is distributed under the Creative Commons Attribution 4.0 International licence. Last version of the model can also be obtained from the INSU-certified service SIROCCO at <https://sirocco.obs-mip.fr>. The RiCoRé sea campaign (2020–2021) dataset can be found at <https://doi.org/10.5281/zenodo.20522323> (Michaud et al., 2026a). Model setup files and forcings of Symphonie can be accessed at <https://doi.org/10.5281/zenodo.20537410> (Michaud and Marsaleix, 2026) and the simulation results here: <https://doi.org/10.5281/zenodo.20536767> (Michaud et al., 2026b).



700 **Appendix A: Table of instruments**

Appendix B: Additional results on other transects

Appendix C: Offshore boundary spectra



Table A1. Moorings and sensors information from north to south. LEG1 corresponds to the first acquisition period for the sensors on the foreshore from 11/16/2020 to 01/13/2021, LEG2 to the second acquisition period for the sensors on the foreshore from 01/14/2021 to 03/31/2021 after the battery change, and LEG3 is one week from 01/11/2021 to 01/15/2021 with 23 additional instruments provided by university partners (LEG3 straddles LEG1 and LEG2).

Transect	Moorings	Sensors	Period	Latitude (WGS84)	Longitude (WGS84)	Sensors depth (LAT)	Height from bed (m)	Type of Acquisition
nearshore	BALEINES	Pressure sensor	LEG1-LEG2	46.244255	-1.565751	2.167	0.105	10 Hz continuous
T1	T1-1	Pressure sensor	LEG1-LEG2	46.237433	-1.563356	2.628	0.105	10 Hz continuous
T1	T1-2	Pressure sensor	LEG1-LEG2	46.237009	-1.565606	2.443	0.105	10 Hz continuous
T1	T1-2BIS	Pressure sensor	LEG1-LEG2	46.237183	-1.564566	2.786	0.105	10 Hz continuous
T1	T1-3	Pressure sensor	LEG1-LEG2	46.236656	-1.567632	1.596	0.105	10 Hz continuous
T1	T1-4	Pressure sensor	LEG1-LEG2	46.236371	-1.569203	1.221	0.1	10 Hz continuous
nearshore	OURS	Pressure sensor	LEG1-LEG2	46.230947	-1.557602	2.795	0.105	10 Hz continuous
nearshore	GRIVEAU	Pressure sensor	LEG1-LEG2	46.226966	-1.552216	2.838	0.105	10 Hz continuous
nearshore	CAROLA	Pressure sensor	LEG1-LEG2	46.21905	-1.54535	2.708	0.105	10 Hz continuous
T2	T2-1	Pressure sensor	LEG1-LEG2	46.211833	-1.542816	2.135	0.105	10 Hz continuous
T2	T2-2	Pressure sensor	LEG1-LEG2	46.2115	-1.544033	2.147	0.105	10 Hz continuous
T2	T2-3	Pressure sensor	LEG1-LEG2	46.2108	-1.547166	2.764	0.105	10 Hz continuous
T2	T2-4	Pressure sensor	LEG1	46.210433	-1.548866	1.923	0.35	10 Hz continuous
T2	T2-5	Pressure sensor	LEG1	46.210066	-1.5504	1.883	0.34	10 Hz continuous
T2	T2-6	Directional wave buoy	LEG1-LEG2	46.20655	-1.616566	1.663	0.12	10 Hz continuous
T2	T2-7	Acoustic wave and current profiler	LEG1-LEG2	46.192983	-1.670083	-24.12	0.58	2.56 Hz continuous
T3	G00	Pressure sensor	LEG3	46.20382533	-1.541647078	2.1895	0.06	2 Hz for bottom pressure and AST. Average interval = 1024 s measurement interval = 3600s
T3	AW1	Pressure sensor	LEG3	46.20517469	-1.536390965	3.37	0.1085	10 Hz continuous
T3	G01	Pressure sensor	LEG3	46.20387547	-1.541399107	2.131	0.074	10 Hz continuous
T3	G02	Pressure sensor	LEG3	46.20395757	-1.540981382	2.1905	0.0545	8 Hz continuous
T3	G03	Pressure sensor	LEG3	46.20406959	-1.540701356	2.1825	0.076	8 Hz continuous
T3	G05	Pressure sensor	LEG3	46.2041636	-1.54007364	2.1015	0.055	8 Hz continuous
T3	G06	Pressure sensor	LEG3	46.20421189	-1.53993409	2.0815	0.07	8 Hz continuous
T3	G07	Pressure sensor	LEG3	46.20438282	-1.53950275	2.3395	0.0755	8 Hz continuous
T3	UHR	Acoustic wave and current profiler	LEG3	46.20440	-1.539381	2.52	0.322	4Hz
T3	G08	Pressure sensor	LEG3	46.20445331	-1.5390713	2.41	0.068	8 Hz continuous
T3	G09	Pressure sensor	LEG3	46.20453022	-1.538747879	2.2485	0.0765	8 Hz continuous
T3	G10	Pressure sensor	LEG3	46.20456767	-1.538550166	2.2085	0.077	8 Hz continuous
T3	G11	Pressure sensor	LEG3	46.20467132	-1.538157471	2.3225	0.075	8 Hz continuous
T3	G12	Pressure sensor	LEG3	46.20483846	-1.537593192	2.311	0.033	8 Hz continuous
T3	PT2	Pressure sensor	LEG3	46.20355486	-1.542737475	1.517	0.03	2 Hz continuous
T3	PT3	Pressure sensor	LEG3	46.20366991	-1.54234913	1.835	0.036	2 Hz continuous
T3	PT4	Pressure sensor	LEG3	46.20374491	-1.541965595	1.939	0.032	2 Hz continuous
nearshore	GRIGNON	Pressure sensor	LEG1-LEG2	46.2013833	-1.5376	3.198	0.105	10 Hz continuous
nearshore	GRANGE	Pressure sensor	LEG1-LEG2	46.2001	-1.5275	3.167	0.105	10 Hz continuous

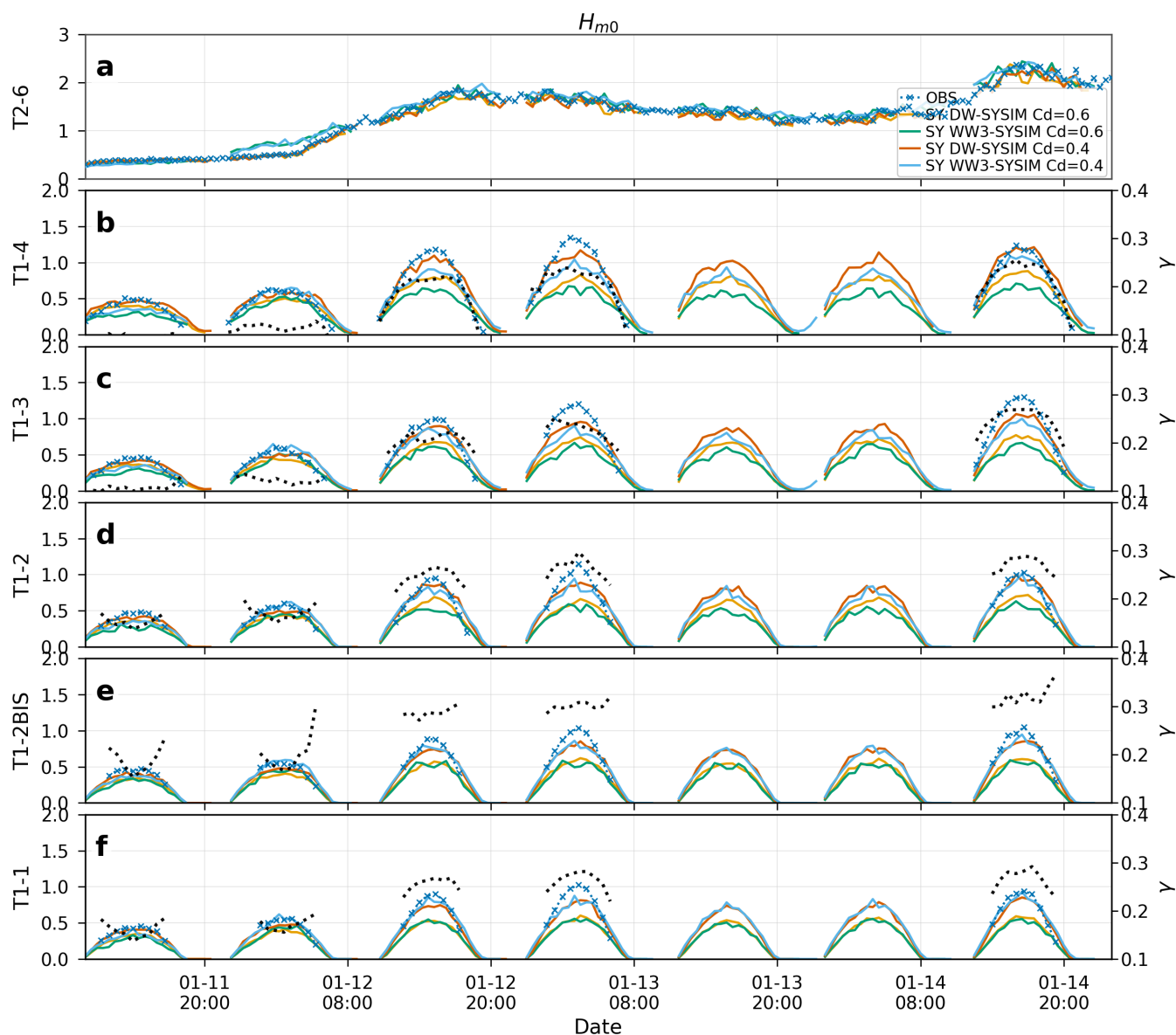


Figure B1. Simulated and observed H_{m0} time series during LEG3 for sensors located offshore (T2-6, a) and in Transect 1 (b: T1-4, c: T1-3, d: T1-2, e: T1-2BIS and f: T1-1). In blue are the observations, in orange the DW-SYSIM simulation with $C_d = 0.6 \text{ m}^{-1}$, in green the WW3-SYSIM simulation with $C_d = 0.6 \text{ m}^{-1}$, in red the DW-SYSIM simulation with $C_d = 0.4 \text{ m}^{-1}$, in cyan the WW3-SYSIM simulation with $C_d = 0.4 \text{ m}^{-1}$. In black, the Miche criteria.

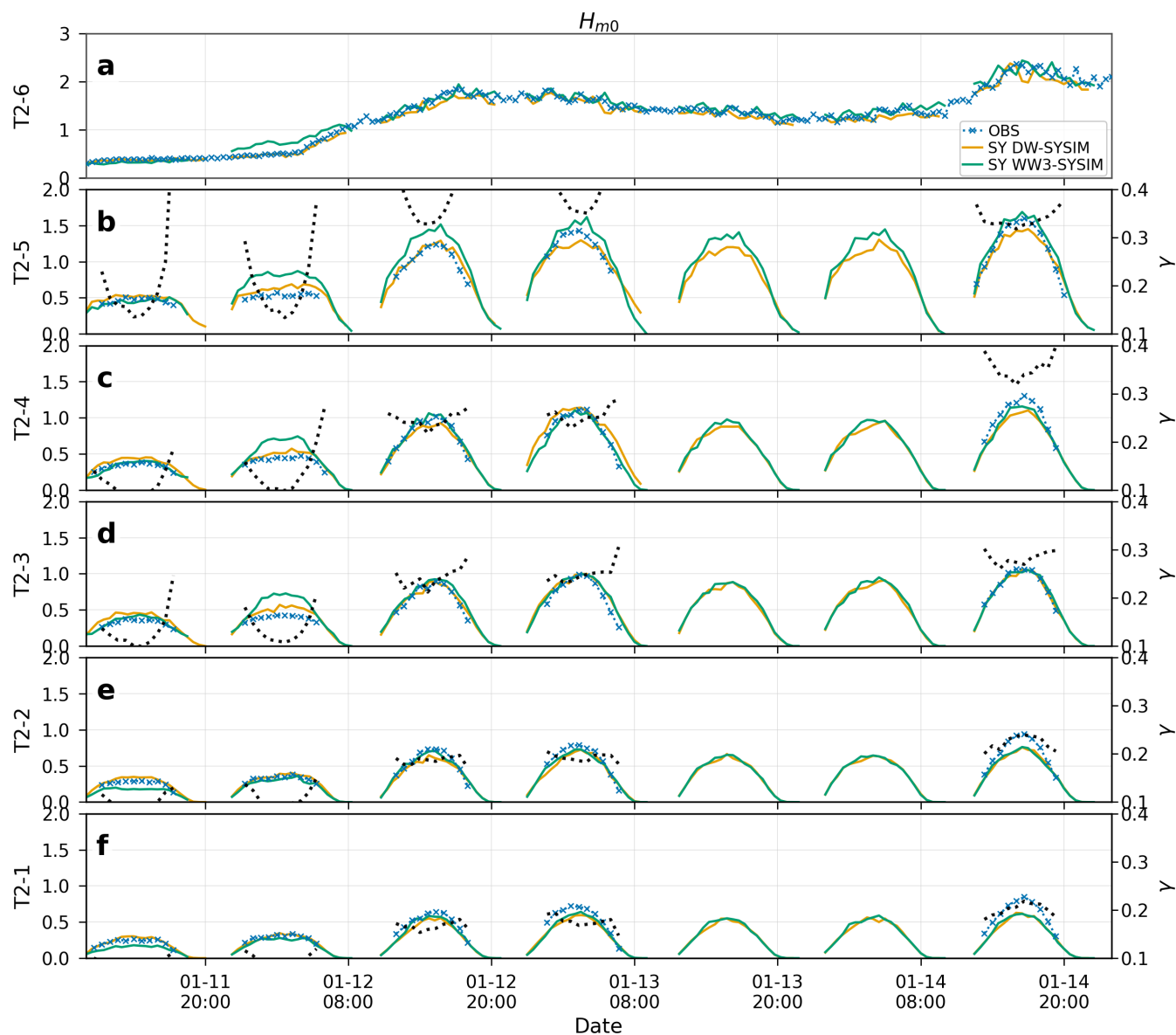


Figure B2. Simulated and observed H_{m0} time series during LEG3 for sensors located offshore (T2-6, a) and in Transect 2 (b: T2-5, c: T2-4, d: T2-3, e: T2-2 and f: T2-1). In blue are the observations, in orange the DW-SYSIM, and in green the WW3-SYSIM simulation. In black, the Miche criteria.

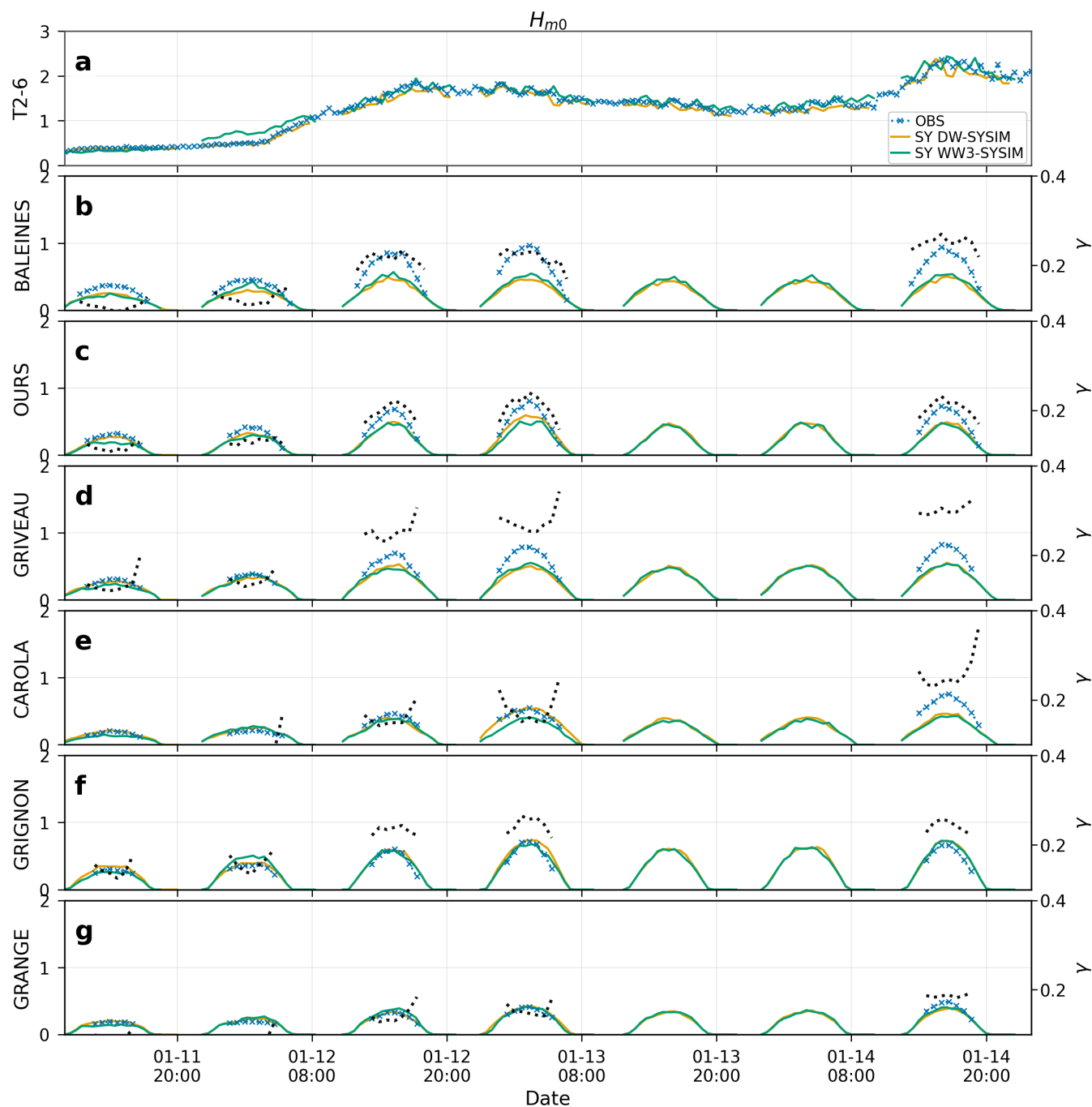


Figure B3. Simulated and observed H_{m0} time series during LEG3 for offshore (T2-6, a) and nearshore instruments along the coast (b: BALEINES, c: OURS, d: GRIVEAU, e: CAROLA, f: GRIGNON and g: GRANGE). In blue are the observations, in orange the DW-SYSIM simulation, and in green the WW3-SYSIM simulation. On top are the simulated and measured values at T2-6, and below the values on nearshore instruments from north to south. In black, the Miche criteria.

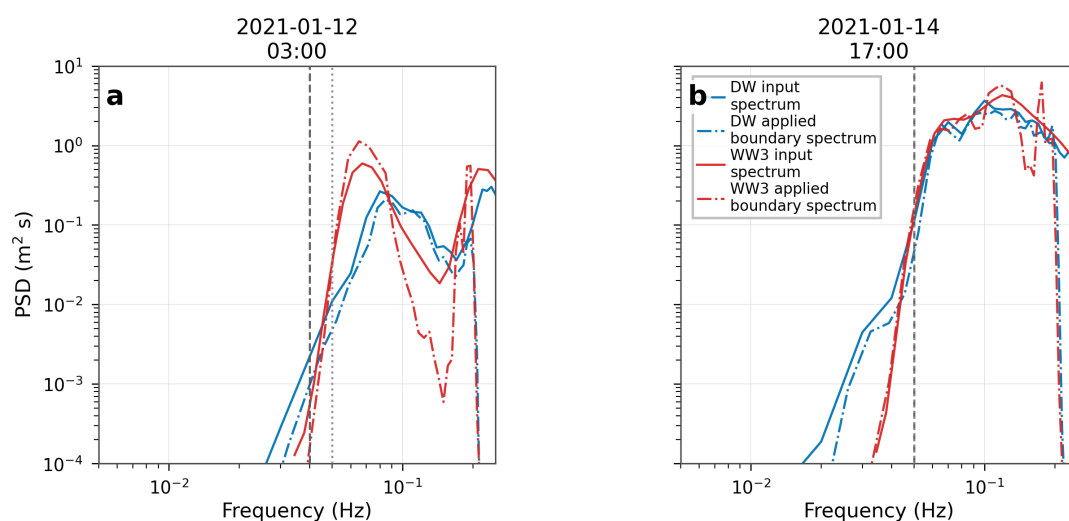


Figure C1. Comparison of the offshore boundary spectra at T2-6 on 12 January 2021 at 03:00 UTC (a) and 14 January 2021 at 17:00 UTC (b). The Datawell and WW3 input spectra are compared with the spectra calculated from the phase-resolving sea-surface-elevation signals actually imposed at the boundary in DW-SYSIM and WW3-SYSIM, respectively. The grey dashed lines indicate the separation between the IG and sea-swell bands, defined as $f_p/2$, and the dotted vertical lines indicate the lower frequency limit of 0.05 Hz used for the frequency de-coherence procedure.



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References

- Akrish, G., Reniers, A., Rijnsdorp, D., Zijlema, M., Rutten, J., and Tissier, M.: The importance of free infragravity waves in the North Sea: Insights from field observations and unstructured SWAN modelling, *Ocean Modelling*, 198, 102619, <https://doi.org/https://doi.org/10.1016/j.ocemod.2025.102619>, 2025.
- Aouf, L., Dalphinet, A., Hauser, D., Delaye, L., Tison, C., Chapron, B., Hermozo, L., and Tourain, C.: On the Assimilation of CFOSAT Wave Data in the Wave Model MFWAM : Verification Phase, in: *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, pp. 7959–7961, <https://doi.org/10.1109/IGARSS.2019.8900180>, 2019.
- Ardhuin, F., Rascle, N., and Belibassakis, K.: Explicit wave-averaged primitive equations using a generalized Lagrangian mean., *Ocean Modelling*, 20, 35–60, 2008.
- Ardhuin, F., Rawat, A., and Aucan, J.: A numerical model for free infragravity waves: Definition and validation at regional and global scales, *Ocean Modelling*, 77, 20–32, <https://doi.org/https://doi.org/10.1016/j.ocemod.2014.02.006>, 2014.
- Athimon, E. and Maanan, M.: Vulnerability, resilience and adaptation of societies during major extreme storms during the Little Ice Age, *Climate of the Past*, 14, 1487–1497, <https://doi.org/10.5194/cp-14-1487-2018>, 2018.
- Barbot, S., Lagarde, M., Lyard, F., Marsaleix, P., Lherminier, P., and Jeandel, C.: Internal Tides Responsible for Lithogenic Inputs Along the Iberian Continental Slope, *Journal of Geophysical Research: Oceans*, 127, e2022JC018816, <https://doi.org/https://doi.org/10.1029/2022JC018816>, e2022JC018816 2022JC018816, 2022.
- Bellafont, F., Morichon, D., Roeber, V., André, G., and Abadie, S.: Infragravity period oscillations in a channel harbor near a river mouth, *Coastal Engineering Proceedings*, 1, papers.8, <https://doi.org/10.9753/icce.v36.papers.8>, 2018.
- Bennis, A., Ardhuin, F., and Dumas, F.: On the coupling of wave and three-dimensional circulation models : Choice of theoretical framework, practical implementation and adiabatic tests, *Ocean Modelling*, 40, 260–272, 2011.
- Bertin, X., Bruneau, N., Breilh, J.-F., Fortunato, A. B., and Karpytchev, M.: Importance of wave age and resonance in storm surges: The case Xynthia, Bay of Biscay, *Ocean Modelling*, 42, 16–30, <https://doi.org/https://doi.org/10.1016/j.ocemod.2011.11.001>, 2012.
- Bertin, X., de Bakker, A., van Dongeren, A., Coco, G., André, G., Ardhuin, F., Bonneton, P., Bouchette, F., Castelle, B., Crawford, W. C., Davidson, M., Deen, M., Dodet, G., Guérin, T., Inch, K., Leckler, F., McCall, R., Muller, H., Olabarrieta, M., Roelvink, D., Ruessink, G., Sous, D., Éléonore Stutzmann, and Tissier, M.: Infragravity waves: From driving mechanisms to impacts, *Earth-Science Reviews*, 177, 774–799, <https://doi.org/https://doi.org/10.1016/j.earscirev.2018.01.002>, 2018.
- Bertin, X., Martins, K., de Bakker, A., Chataigner, T., Guérin, T., Coulombier, T., and de Viron, O.: Energy transfers and reflection of infragravity waves at a dissipative beach under storm waves, *Journal of Geophysical Research: Oceans*, 125, e2019JC015714, 2020.
- Bishop, C. T. and Donelan, M. A.: Measuring waves with pressure transducers, *Coastal Engineering*, 11, 309–328, [https://doi.org/10.1016/0378-3839\(87\)90031-7](https://doi.org/10.1016/0378-3839(87)90031-7), 1987.
- Blayo, E. and Debreu, L.: Revisiting open boundary conditions from the point of view of characteristic variables, *Ocean Modelling*, 9, 231–252, <https://doi.org/10.1016/j.ocemod.2004.07.001>, 2005.
- Blumberg, A. F. and Kantha, L. H.: Open Boundary Condition for Circulation Models, *Journal of Hydraulic Engineering*, 111, 237–255, [https://doi.org/10.1061/\(ASCE\)0733-9429\(1985\)111:2\(237\)](https://doi.org/10.1061/(ASCE)0733-9429(1985)111:2(237)), 1985.
- Bonneton, P., Lannes, D., Martins, K., and Michallet, H.: A nonlinear weakly dispersive method for recovering the elevation of irrotational surface waves from pressure measurements, *Coastal Engineering*, 138, 1–8, <https://doi.org/10.1016/j.coastaleng.2018.04.005>, 2018.



- Booij, N., Ris, R. C., and Holthuijsen, L. H.: A third-generation wave model for coastal regions: 1. Model description and validation, *Journal of Geophysical Research*, 104(C4), 7649–7666, <https://doi.org/10.1029/98jc02622>, 1999.
- 755 Breilh, J.-F., Bertin, X., Éric Chaumillon, Giloy, N., and Sauzeau, T.: How frequent is storm-induced flooding in the central part of the Bay of Biscay?, *Global and Planetary Change*, 122, 161–175, <https://doi.org/10.1016/j.gloplacha.2014.08.013>, 2014.
- Chauveau, E., Chadenas, C., Comentale, B., Pottier, P., Blanlœil, A., Feuillet, T., Mercier, D., Pourinet, L., Rollo, N., Tillier, I., et al.: *Xynthia: leçons d’une catastrophe*, Cybergeog: European Journal of Geography, 2011.
- Chen, Q., Kirby, J., Dalrymple, R., F. Shi, F., and Thornton, E. B.: Boussinesq modeling of longshore currents, *J. Geophys. Res.*, 108(C11), 3362, <https://doi.org/10.1029/2002JC001308>, 2003.
- 760 Craig, P. D. and Banner, M. L.: Modeling Wave-Enhanced Turbulence in the Ocean Surface Layer, *Journal of Physical Oceanography*, 24, 2546 – 2559, [https://doi.org/10.1175/1520-0485\(1994\)024<2546:MWETIT>2.0.CO;2](https://doi.org/10.1175/1520-0485(1994)024<2546:MWETIT>2.0.CO;2), 1994.
- Crawford, W., Ballu, V., Bertin, X., and Karpytchev, M.: The sources of deep ocean infragravity waves observed in the North Atlantic Ocean, *Journal of Geophysical Research: Oceans*, 120, 5120–5133, <https://doi.org/10.1002/2014JC010657>, 2015.
- 765 de Beer, A., McCall, R., Long, J., Tissier, M., and Reniers, A.: Simulating wave runoff on an intermediate–reflective beach using a wave-resolving and a wave-averaged version of XBeach, *Coastal Engineering*, 163, 103 788, <https://doi.org/10.1016/j.coastaleng.2020.103788>, 2021.
- Dealbera, S., Sous, D., Morichon, D., and Michaud, H.: The role of roughness geometry in frictional wave dissipation, *Coastal Engineering*, 189, 104 478, <https://doi.org/10.1016/j.coastaleng.2024.104478>, 2024.
- 770 Dinar, A., Esteban, E., Calvo, E., Herrera, G., Teatini, P., Tomás, R., Li, Y., Ezquerro, P., and Albiac, J.: We lose ground: Global assessment of land subsidence impact extent, *Science of The Total Environment*, 786, 147 415, <https://doi.org/10.1016/j.scitotenv.2021.147415>, 2021.
- Filippini, A., Arpaia, L., Perrier, V., Pedreros, R., Bonneton, P., Lannes, D., Marche, F., De Brye, S., Delmas, S., Lecacheux, S., Boulahya, F., and Ricchiuto, M.: An operational discontinuous Galerkin shallow water model for coastal flood assessment, *Ocean Modelling*, 192, 102 447, <https://doi.org/10.1016/j.ocemod.2024.102447>, 2024.
- 775 Geindre, M., Sous, D., Michaud, H., Floc’h, F., Bertin, X., Aubry, A., Jeanson, M., and Pezerat, M.: Wave Friction Factor and Roughness Definition in Multi-Scale Coral Barrier Reef, *Journal of Geophysical Research: Oceans*, 130, e2025JC023 146, <https://doi.org/10.1029/2025JC023146>, e2025JC023146 2025JC023146, 2025.
- Gravelle, M., Wöppelmann, G., Gobron, K., Altamimi, Z., Guichard, M., Herring, T., and Rebischung, P.: The ULR-repro3 GPS data reanalysis and its estimates of vertical land motion at tide gauges for sea level science, *Earth System Science Data*, 15, 497–509, <https://doi.org/10.5194/essd-15-497-2023>, 2023.
- 780 Grebenkov, D. S. and Serró, J.: Following a trend with an exponential moving average: Analytical results for a Gaussian model, *Physica A: Statistical Mechanics and its Applications*, 394, 288–303, <https://doi.org/10.1016/j.physa.2013.10.007>, 2014.
- Group, T. W. I. D.: User manual and system documentation of WAVEWATCH III version 6.07, <https://polar.ncep.noaa.gov/waves/wavewatch/manual.v5.16.pdf>, 2019.
- 785 Guélard Ancilotti, E., Sous, D., Morichon, D., Marsaleix, P., Michaud, H., and Déalbera, S.: Modélisation à phase résolue de la transformation des vagues en zone de déferlement sur des fonds rugueux idéalisés, in: XVIIIèmes Journées Nationales Génie Côtier Génie Civil, Anglet, Editions Paralia, <https://doi.org/10.5150/jngcgc.2024.007>, 2024.
- Henderson, C. S., Fiedler, J. W., Merrifield, M. A., Guza, R., and Young, A. P.: Phase resolving runoff and overtopping field validation of SWASH, *Coastal Engineering*, 175, 104 128, <https://doi.org/10.1016/j.coastaleng.2022.104128>, 2022.



- 790 Imbertie, E.: Characterization of the impact of storm wave overtopping on a vertical structure at the top of an upper-beach dike based on field measurements and phase-resolving depth-integrated numerical modeling, Theses, Université de Pau et des Pays de l'Adour, <https://theses.hal.science/tel-04902203>, 2024.
- Jourdan, D., Caillaud, E., Pasquet, A., Michaud, H., and Paradis, D.: Prévion et avertissement du risque de submersion marine : la Vigilance vagues-submersion, pp. 54–60, AFT - association francophone de topographie, 2023.
- 795 Kennedy, A. B., Chen, Q., Kirby, J. T., and Dalrymple, R. A.: Boussinesq Modeling of Wave Transformation, Breaking, and Runup. I: 1D, Journal of Waterway, Port, Coastal, and Ocean Engineering, 126, 39–47, [https://doi.org/10.1061/\(ASCE\)0733-950X\(2000\)126:1\(39\)](https://doi.org/10.1061/(ASCE)0733-950X(2000)126:1(39)), 2000.
- Kergadallan, X.: Candhis : analyses 2024 des états de mer Tome 1 - Mer du Nord, Manche et Atlantique, Tech. rep., CEREMA, 2024.
- Kinsman, B.: Wind Waves: Their Generation and Propagation on the Ocean Surface, Courier Dover Publications, 1965.
- 800 Kirby, J. T., Wei, G., Chen, Q., Kennedy, A. B., and Dalrymple, R. A.: FUNWAVE 1.0, Fully nonlinear Boussinesq wave model. Documentation and users manual, Tech. rep., Report CACR98-06, Center for Applied Coastal Research, University of Delaware, 1998.
- Knutson, T. R., Chung, M. V., Vecchi, G., Sun, J., Hsieh, T.-L., and Smith, A. J. P.: Critical Issues in Climate Change Science, chap. ScienceBrief Review:Climate change is probably increasing the intensity of tropical cyclones, edited by: Corinne Le Quéré, Peter Liss and Piers Forster, <https://doi.org/10.5281/zenodo.4570334>, 2021.
- 805 Lange, A. M. Z., Fiedler, J. W., Merrifield, M. A., and Guza, R. T.: Free Infragravity Waves on the Inner Shelf: Observations and Parameterizations at Two Southern California Beaches, Journal of Geophysical Research: Oceans, 129, e2023JC020378, <https://doi.org/10.1029/2023JC020378>, e2023JC020378 2023JC020378, 2024.
- Le Goff Le Gourriec, L., Michaud, H., Sous, D., Déalbera, S., Bouchette, F., Bertin, X., Marsaleix, P., Seyfried, L., Leballeur, L., Krien, Y., Meulé, S., Lavaud, L., Pasquet, A., Biscara, L., and Brosse, F.: Transformation des vagues et processus de dissipation sur une côte rocheuse : premiers résultats issus de la campagne de terrain RiCoRé”, in: XVIIèmes Journées Nationales Génie Côtier Génie Civil, Chatou, Editions Paralia, <https://doi.org/10.5150/jngcgc.2022.011>, 2022.
- 810 Lee, J. W., Teubner, M. D., Nixon, J. B., and Gill, P. M.: Applications of the artificial compressibility method for turbulent open channel flows, International Journal for Numerical Methods in Fluids, 51, 617–633, <https://doi.org/10.1002/flid.1137>, 2006.
- 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/https://doi.org/10.1016/0011-7471\(64\)90001-4](https://doi.org/https://doi.org/10.1016/0011-7471(64)90001-4), 1964.
- 815 Longuet-Higgins, M. S. and Stewart, R. W.: Radiation stress and mass transport in gravity waves, with application to ‘surf beats’, Journal of Fluid Mechanics, 13, 481–504, <https://doi.org/10.1017/S0022112062000877>, 1962.
- Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N.: FES2014 global ocean tide atlas: design and performance, Ocean Science, 17, 615–649, <https://doi.org/10.5194/os-17-615-2021>, 2021.
- 820 Marchesiello, P., Auclair, F., Debreu, L., McWilliams, J., Almar, R., Benshila, R., and Dumas, F.: Tridimensional nonhydrostatic transient rip currents in a wave-resolving model, Ocean Modelling, 163, 101 816, <https://doi.org/10.1016/j.ocemod.2021.101816>, 2021.
- Marsaleix, P., Auclair, F., and Estournel, C.: Considerations on Open Boundary Conditions for Regional and Coastal Ocean Models, Journal of Atmospheric and Oceanic Technology, 23, 1604 – 1613, <https://doi.org/10.1175/JTECH1930.1>, 2006.
- Marsaleix, P., Michaud, H., and Estournel, C.: 3D phase-resolved wave modelling with a non-hydrostatic ocean circulation model, Ocean Modelling, 136, 28–50, <https://doi.org/10.1016/j.ocemod.2019.02.002>, 2019.
- 825



- Marsaleix, P., Michaud, H., and Seyfried, L.: Adaptation d'un modèle de circulation océanique à la modélisation déterministe de la houle : application à la plage de Sète, in: XVIèmes Journées Nationales Génie Côtier Génie Civil, Le Havre, Editions Paralia, <https://doi.org/10.5150/jngcgc.2020.012>, 2020.
- Marsaleix, P., Michaud, H., Sous, D., and Guélaud Ancilotti, E.: Symphonie v3.8.9, <https://doi.org/10.5281/zenodo.20527266>, 2026.
- 830 Martins, K., Bonneton, P., Mouragues, A., and Castelle, B.: Non-hydrostatic, Non-linear Processes in the Surf Zone, *Journal of Geophysical Research: Oceans*, 125, <https://doi.org/10.1029/2019jc015521>, 2020.
- Martins, K., Bertin, X., Mengual, B., Pezerat, M., Lavaud, L., Guérin, T., and Zhang, Y. J.: Wave-induced mean currents and setup over barred and steep sandy beaches, *Ocean Modelling*, 179, 102 110, <https://doi.org/https://doi.org/10.1016/j.ocemod.2022.102110>, 2022.
- McCall, R., Masselink, G., Poate, T., Roelvink, J., Almeida, L., Davidson, M., and Russell, P.: Modelling storm hydrodynamics on gravel
 835 beaches with XBeach-G, *Coastal Engineering*, 91, 231–250, <https://doi.org/https://doi.org/10.1016/j.coastaleng.2014.06.007>, 2014.
- 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.
- Michaud, H. and Marsaleix, P.: Symphonie configuration and forcings files for the RiCoRé sea campaign (2020-2021) simulation, <https://doi.org/10.5281/zenodo.20537410>, 2026.
- 840 Michaud, H., Marsaleix, P., Leredde, Y., Estournel, C., Bourrin, F., Lyard, F., Mayet, C., and Ardhuin, F.: Three-dimensional modelling of wave-induced current from the surf zone to the inner shelf, *Ocean Science*, 8, 657–681, <https://doi.org/10.5194/os-8-657-2012>, 2012.
- Michaud, H., Pasquet, A., Baraille, R., Leckler, F., Aouf, A., Dalphiné, A., Huchet, M., Roland, A., Dutour-Sikiric, M., Ardhuin, F., and Filipot, J.: Implementation of the new French operational coastal wave forecasting system and application to a wave-current interaction study, in: 14th International Workshop on Wave Hindcasting and Forecasting & 5th Coastal Hazard Symposium, 2015.
- 845 Michaud, H., Bouchette, F., Sous, D., Meulé, S., Bertin, X., and Marsaleix, P.: RiCoRé sea campaign (2020-2021) dataset, <https://doi.org/10.5281/zenodo.20522323>, 2026a.
- Michaud, H., Marsaleix, P., and Sous, D.: Symphonie results for the RiCoRé sea campaign (2020-2021) LEG3, <https://doi.org/10.5281/zenodo.20536767>, 2026b.
- Mihami, F.-Z., Roeber, V., and Morichon, D.: Efficient Numerical Computations of Long-Wave Run-Up and Their Sensitivity to Grid Nesting, *Water Waves*, 4, 517–548, <https://doi.org/10.1007/s42286-022-00070-8>, 2022.
- 850 Nicolae-Lerma, A., Pedrero, R., Robinet, A., and Sénéchal, N.: Simulating wave setup and runup during storm conditions on a complex barred beach, *Coastal Engineering*, 123, 29–41, <https://doi.org/10.1016/j.coastaleng.2019.04.006>, 2017.
- Oliveira, A., Fortunato, A. B., Rodrigues, M., Azevedo, A., Rogeiro, J. a., Bernardo, S., Lavaud, L., Bertin, X., Nahon, A., de Jesus, G., Rocha, M., and Lopes, P.: Forecasting contrasting coastal and estuarine hydrodynamics with OPENCoastS, *Environ. Model. Softw.*, 143, <https://doi.org/10.1016/j.envsoft.2021.105132>, 2021.
- 855 Oppenheimer, M., Glavovic, B., Hinkel, J., de Wal, R. V., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., Deconto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., and Sebesvari, Z.: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, chap. Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities, O. Pörtner et al. (eds.)). World Meteorological Organization, Geneva, 2019.
- 860 Orlanski, I.: A simple boundary condition for unbounded hyperbolic flows, *Journal of Computational Physics*, 21, 251–269, [https://doi.org/10.1016/0021-9991\(76\)90023-1](https://doi.org/10.1016/0021-9991(76)90023-1), 1976.



- Pairaud, I., Lyard, F., Auclair, F., Letellier, T., and Marsaleix, P.: Dynamics of the semi-diurnal and quarter-diurnal internal tides in the Bay of Biscay. Part 1: Barotropic tides, *Continental Shelf Research*, 28, 1294–1315, <https://doi.org/https://doi.org/10.1016/j.csr.2008.03.004>, 2008.
- 865 Pinault, J., Morichon, D., Delpey, M., and Roeber, V.: Field observations and numerical modeling of swash motions at an engineered embayed beach under moderate to energetic conditions, *Estuarine, Coastal and Shelf Science*, 279, 108 143, <https://doi.org/https://doi.org/10.1016/j.ecss.2022.108143>, 2022.
- Portilla, J., Ocampo-Torres, F. J., and Monbaliu, J.: Spectral Partitioning and Identification of Wind Sea and Swell, *Journal of Atmospheric and Oceanic Technology*, 26, 107–122, <https://doi.org/10.1175/2008JTECHO609.1>, 2009.
- 870 Richard, G.: An extension of the Boussinesq-type models to weakly compressible flows, *European Journal of Mechanics - B/Fluids*, pp. 217–240, 2021.
- Roeber, V. and Cheung, K. F.: Boussinesq-type model for energetic breaking waves in fringing reef environments, *Coastal Engineering*, 70, 1–20, <https://doi.org/https://doi.org/10.1016/j.coastaleng.2012.06.001>, 2012.
- Salatin, R., Chen, Q., Bak, A. S., Shi, F., and Brandt, S. R.: Effects of Wave Coherence on Longshore Variability of Nearshore Wave Processes, *Journal of Geophysical Research: Oceans*, 126, e2021JC017 641, <https://doi.org/https://doi.org/10.1029/2021JC017641>, e2021JC017641 2021JC017641, 2021.
- 875 Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F., Lac, C., and Masson, V.: The AROME-France Convective-Scale Operational Model, *Monthly Weather Review*, 139, 976 – 991, <https://doi.org/10.1175/2010MWR3425.1>, 2011.
- Seyfried, L., Biscara, L., Michaud, H., Leckler, F., Pasquet, A., Pezerat, M., and Gicquel, C.: Insights from a topo-bathymetric and oceanographic dataset for coastal flooding studies: the French Flooding Prevention Action Program of Saint-Malo, *Earth Syst. Sci. Data*, 16, 3345–3367, <https://doi.org/10.5194/essd-16-3345-2024>, 2024.
- 880 Shom: MNT topo-bathymétrie côtier des abords de l’île de Ré (Projet HOMONIM-3), https://doi.org/10.17183/MNT_COTIER_ILE_DE_RE_HOMONIM_5m_WGS84, 2024.
- Smit, P., Stelling, G., Roelvink, D., Van Thiel de Vries, J., McCall, R., Van Dongeren, A., Zwinkels, C., and Jacobs, R.: XBeach: Non-hydrostatic model, Delft University of Technology and Deltares, 2010.
- 885 Smith, J. A.: Wave–Current Interactions in Finite Depth, *Journal of Physical Oceanography*, 36, 1403 – 1419, <https://doi.org/10.1175/JPO2911.1>, 2006.
- Sous, D., Meulé, S., Dealbera, S., Michaud, H., Gassier, G., Pezerat, M., and Bouchette, F.: Quantifying the topographical structure of rocky and coral seabeds, *PLOS ONE*, 19, 1–28, <https://doi.org/10.1371/journal.pone.0303422>, 2024.
- 890 Torres-Freyermuth, A., Mariño Tapia, I., Coronado, C., Salles, P., Medellín, G., Pedrozo-Acuña, A., Silva, R., Candela, J., and Iglesias-Prieto, R.: Wave-induced extreme water levels in the Puerto Morelos fringing reef lagoon, *Natural Hazards and Earth System Sciences*, 12, 3765–3773, <https://doi.org/10.5194/nhess-12-3765-2012>, 2012.
- Toublanc, F., Ayoub, N., Lyard, F., Marsaleix, P., and Allain, D.: Tidal downscaling from the open ocean to the coast: a new approach applied to the Bay of Biscay, *Ocean Modelling*, 124, 16–32, <https://doi.org/https://doi.org/10.1016/j.ocemod.2018.02.001>, 2018.
- 895 Treguier, A. M., Barnier, B., de Miranda, A. P., Molines, J. M., Grima, N., Imbard, M., Madec, G., Messenger, C., Reynaud, T., and Michel, S.: An eddy-permitting model of the Atlantic circulation: Evaluating open boundary conditions, *Journal of Geophysical Research: Oceans*, 106, 22 115–22 129, <https://doi.org/https://doi.org/10.1029/2000JC000376>, 2001.
- Treillou, S., Marchesiello, P., and Baker, C. M.: Correction of coherent interference in wave-resolving nearshore models and validation with experimental data, *Ocean Modelling*, 189, 102 369, <https://doi.org/https://doi.org/10.1016/j.ocemod.2024.102369>, 2024.



- 900 Valcke, S., Craig, T., and Coquart, L.: OASIS3-MCT User Guide, OASIS3-MCT 3.0, Tech. Rep. TR/CMGC/15/38, CERFACS/CNRS SUC
URA No1875, Toulouse, France, 2015.
- Vasarmidis, P., Stratigaki, V., Suzuki, T., Zijlema, M., and Troch, P.: On the accuracy of internal wave generation method in
a non-hydrostatic wave model to generate and absorb dispersive and directional waves, *Ocean Engineering*, 219, 108 303,
<https://doi.org/https://doi.org/10.1016/j.oceaneng.2020.108303>, 2021.
- 905 Vasarmidis, P., Klonaris, G., Zijlema, M., Stratigaki, V., and Troch, P.: A study of the non-linear properties
and wave generation of the multi-layer non-hydrostatic wave model SWASH, *Ocean Engineering*, 302, 117 633,
<https://doi.org/https://doi.org/10.1016/j.oceaneng.2024.117633>, 2024.
- Willmott, C.: On the validation of models., *Physical Geography*, 2, 184–194, 1981.
- Wöppelmann, G. and Marcos, M.: Vertical land motion as a key to understanding sea level change and variability, *Reviews of Geophysics*,
910 54, 64–92, <https://doi.org/https://doi.org/10.1002/2015RG000502>, 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/https://doi.org/10.1016/j.coastaleng.2011.05.015>, 2011.