# A Hybrid Modelling Framework for solving Nearshore Hydrodynamics

Beatriz Pérez-Díaz, Alba Ricondo, Laura Cagigal, Manuel Zornoza-Aguado, Valvanuz Fernandez-Quiruelas, Pablo Alonso-Alguacil, Fernando Méndez, Sonia Castanedo

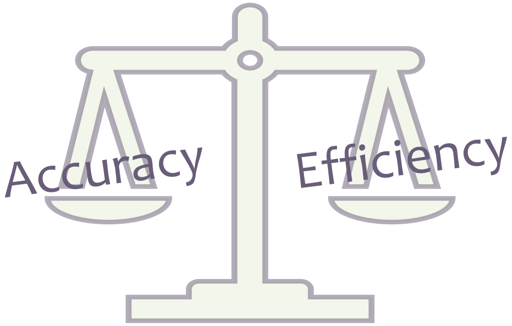
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

4TH INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES, AND COASTAL HAZARDS
Incorporating the 18th International Waves Workshop

# Motivation

Marzo 2014. Somo (Cantabria)

Need to improve the downscaling of surf zone hydrodynamics



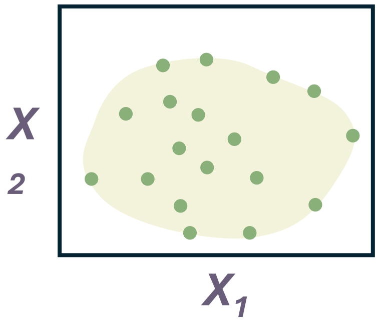

Majuro airport, Republic of the Marshall Islands

(Source: Dr. Murray Ford, the University of Auckland, New Zealand)

Photo credit: Samoa Meteorological Service

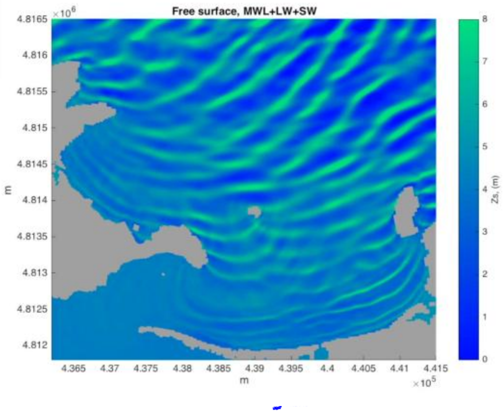
# Hybrid Downscaling

Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA



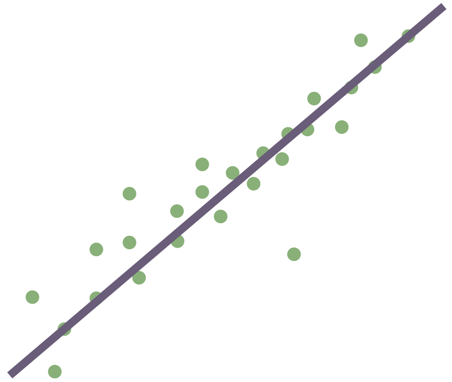

**Sampling & Selection techniques**

Hypercube
Random sampling
Latin Hypercube S.
Sobol
MDA




**Modeling techniques**

Numerical models (SWAN, XBeach, SWASH, Delft3D, ADCIRC, SCHISM, LisFlood, SFINCS)



**Reconstruction**

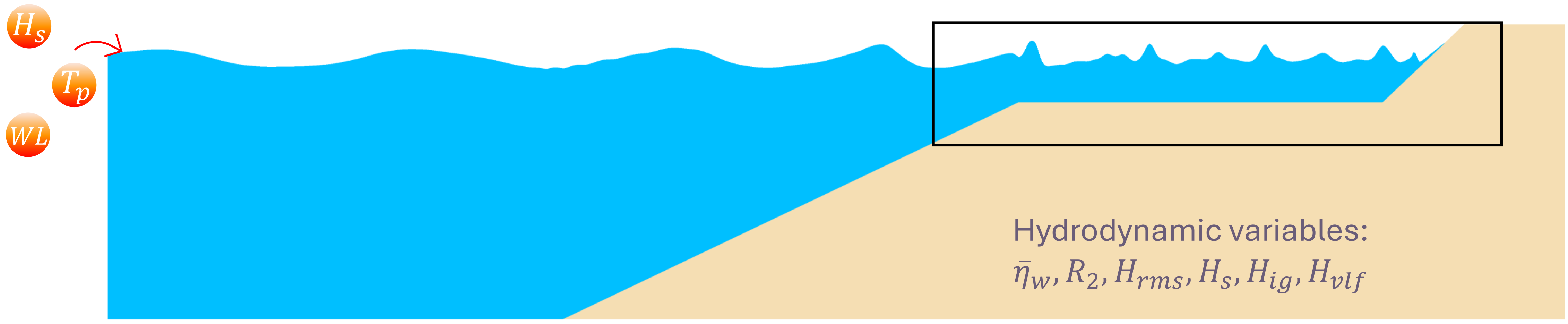
Look-up tables
Interpolation
Regression methods
Neural networks

# Hybrid models

| | | |
|---|---|---|
| ➢ Modeling surf-zone hydrodynamics 1D | **HySwash** | *Ricondo et al., 2024 Oeng*<br>*Ricondo et al., 2024 Ceng* |
| ➢ Automatic Calibration of Hydrodynamic models | **CHySwash** | *Pérez-Díaz et al., (in prep)* |
| ➢ Assessment of nature-based solutions | **HyVeggy** | *Valvanuz et al., (in prep)* |
| ➢ Modeling surf-zone hydrodynamics 2D | **HyWaTHy** | *Zornoza et al., 2025 CEng* |
| ➢ Modeling of wind and wind waves | **HyWindSea** | *Bellido et al., (in prep)* |
| ➢ Salt-Wedge Intrusion | **HySalt** | *Jimenez et al., (in prep)* |
| ➢ Compound Coastal Flooding | **HyFlood** | *Ortiz-Angulo et al., (in prep)* |
| ➢ Tropical Cyclone Inundation | **ShyTCWaves** | *van Vloten et al., 2024* |

# HySwash

Downscaling hydrodynamic variables along cross-shore profiles




## Sampling and Selection

**LHS**

**LATIN HYPERCUBE SAMPLING**
Sampling Technique of Nearshore Wave Conditions (*N* cases)

**MDA**

**MAXIMUM DISSIMILARITY ALGORITHM**
Clustering Algorithm (selection of *M* cases)

## Modeling

**NUM. MODEL**

Simulations (e.g. SWASH, Xbeach)

## Reconstruction

**PCA**

**PRINCIPAL COMPONENT ANALYSIS**
Dimensionality Reduction

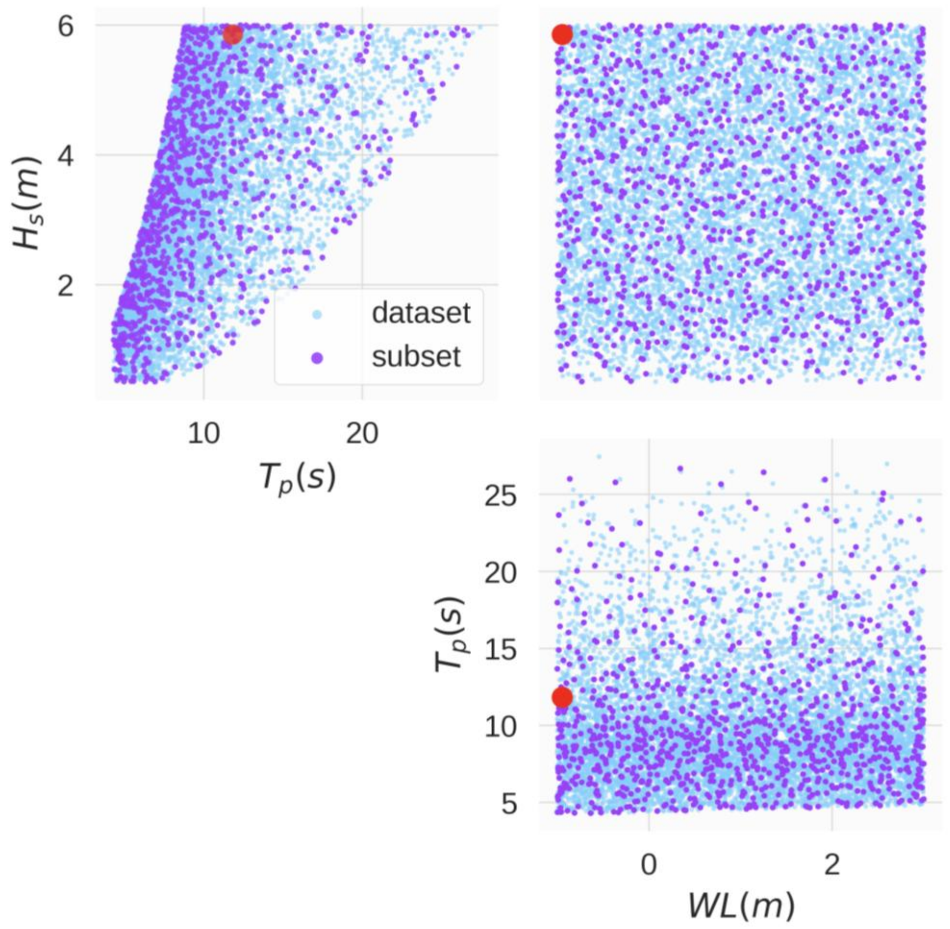
**RBF**

**RADIAL BASIS FUNCTIONS**
Interpolation Algorithm

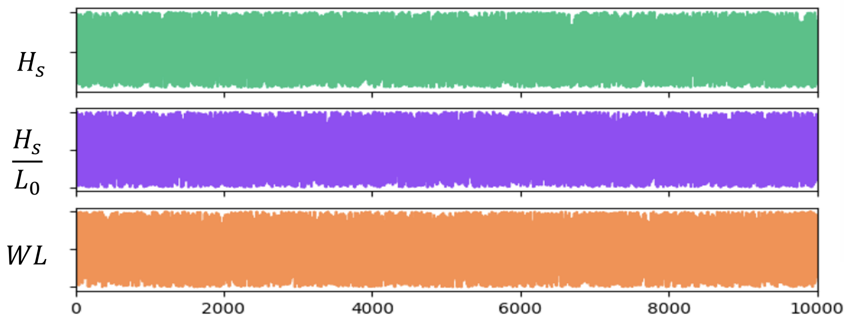
# HySwash. Sampling and selection

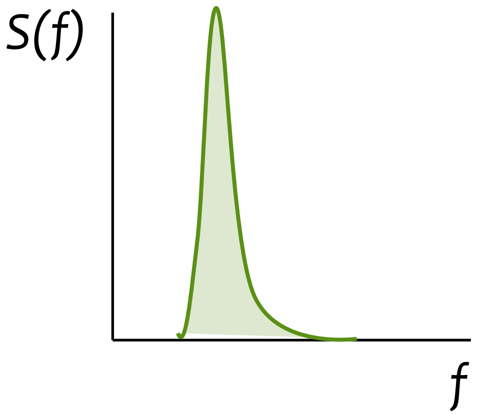
**LHS + MDA**

Candidate sampling size M = 1000




| Var | Range | |
|---|---|---|
| $H_s$ | 0.5 | 3 |
| $WL$ | -1 | 1 |
| $\frac{H_s}{L_0}$ | 0.005 | 0.5 |



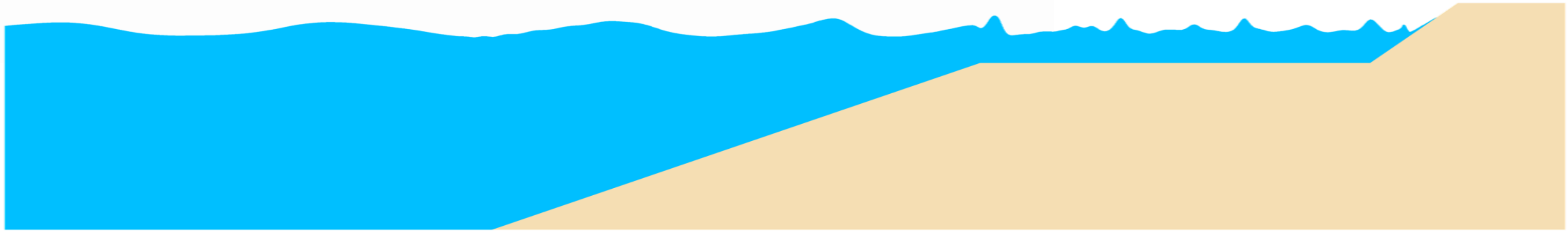

TMA spectrum

JONSWAP * $f$(wave frequency, water depth)

Hydraulic boundary conditions for SWASH

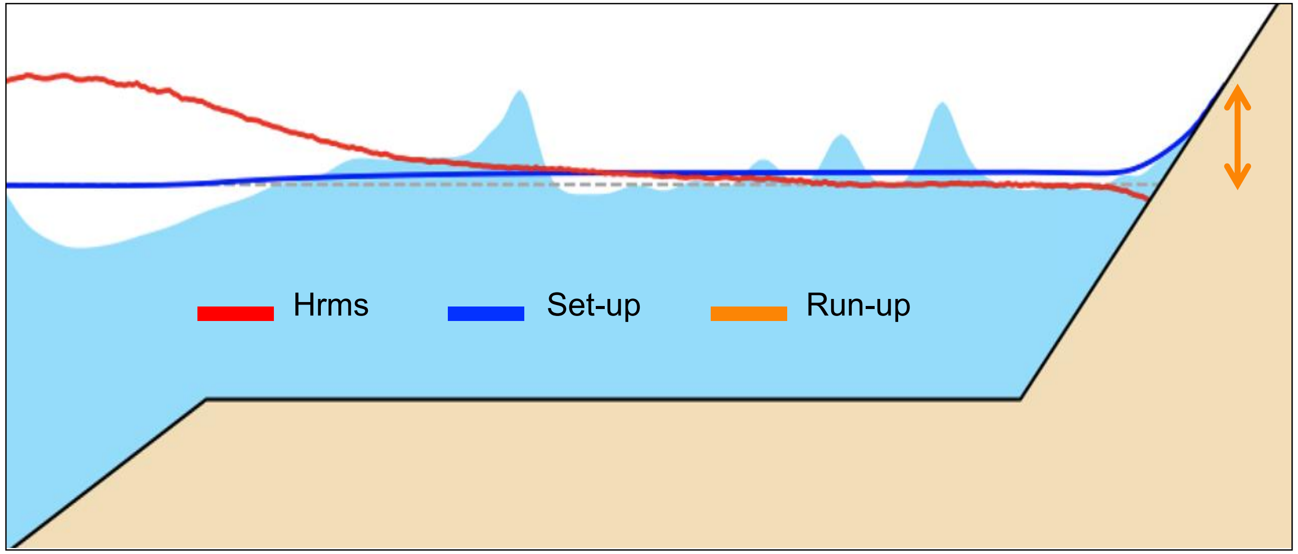
# HySwash. Numerical modelling

1000 numerical simulation with Swash model (version 8.01) (Zijlema et al., 2011)



- **Computational grid**
  60 nodes per wavelength
- **Boundary conditions**
  TMA spectra as Surface elevation
  Weakly reflective W
  Radiation E
  Manning coefficient of 0.002
- **Numerical parameters**
  Non-hydrostatic 1D mode
  2 vertical layers
  4 hours of simulation
  Automatic time integration (courant 0.1-0.5)
- **Post-processed output quantities**
  2% Run-up
  Msetup
  Hrms
  Hss (1-25s), Hig (25-250s), Hvlf (250-1000s)

SWASH model (version 8.01) *(Zijlema et al., 2011)*



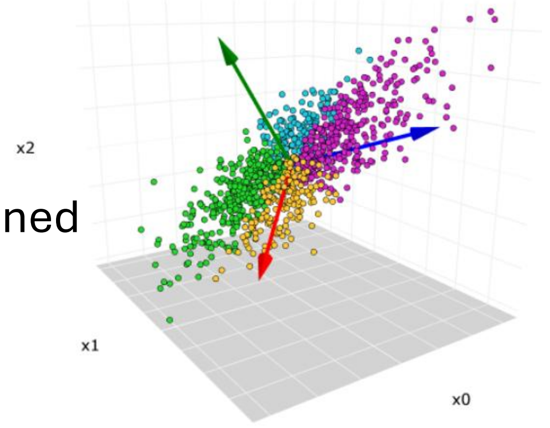
# HySwash. Reconstruction

**Swash Output**
Synthetic library of M cases

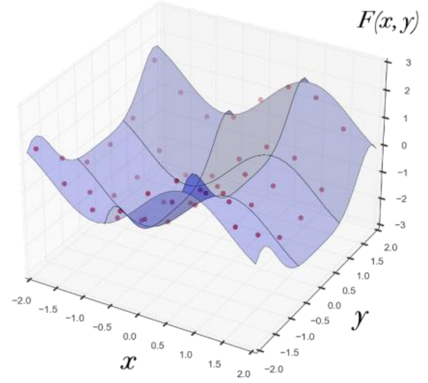
**PCA**
**PRINCIPAL COMPONENT ANALYSIS**
Dimensionality Reduction

**RBF**
**RADIAL BASIS FUNCTIONS**
Interpolation Algorithm

99.8% explained variance



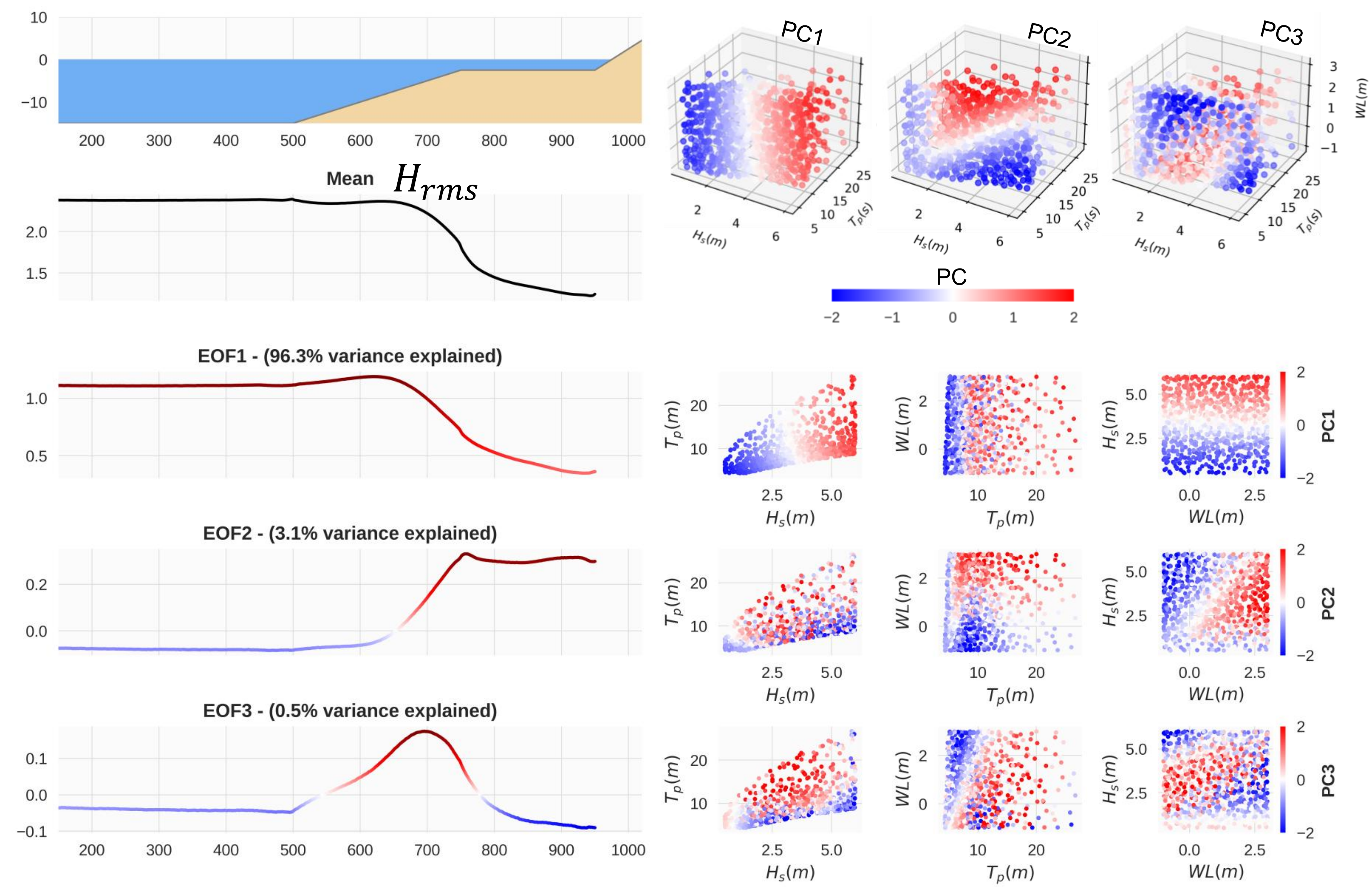

Camus et al., 2011




$$y(x;\ H_s, H_s/L_o\,, \eta) \approx \bar{y}(x) + EOF_1(x)PC_1(H_s, H_s/L_o\,, \eta) + \ldots + EOF_C(x)PC_C(H_s, H_s/L_o\,, \eta)$$

$$H_{rms}(x;\ H_s, H_s/L_o\,, \eta)$$
$$H_{ig}(x;\ H_s, H_s/L_o\,, \eta)$$
$$\bar{\eta}(x;\ H_s, H_s/L_o\,, \eta)$$

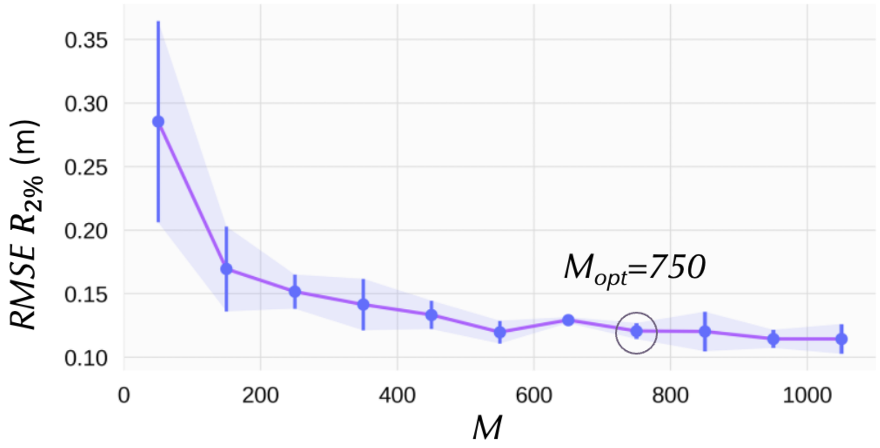
# HySwash: Reconstruction

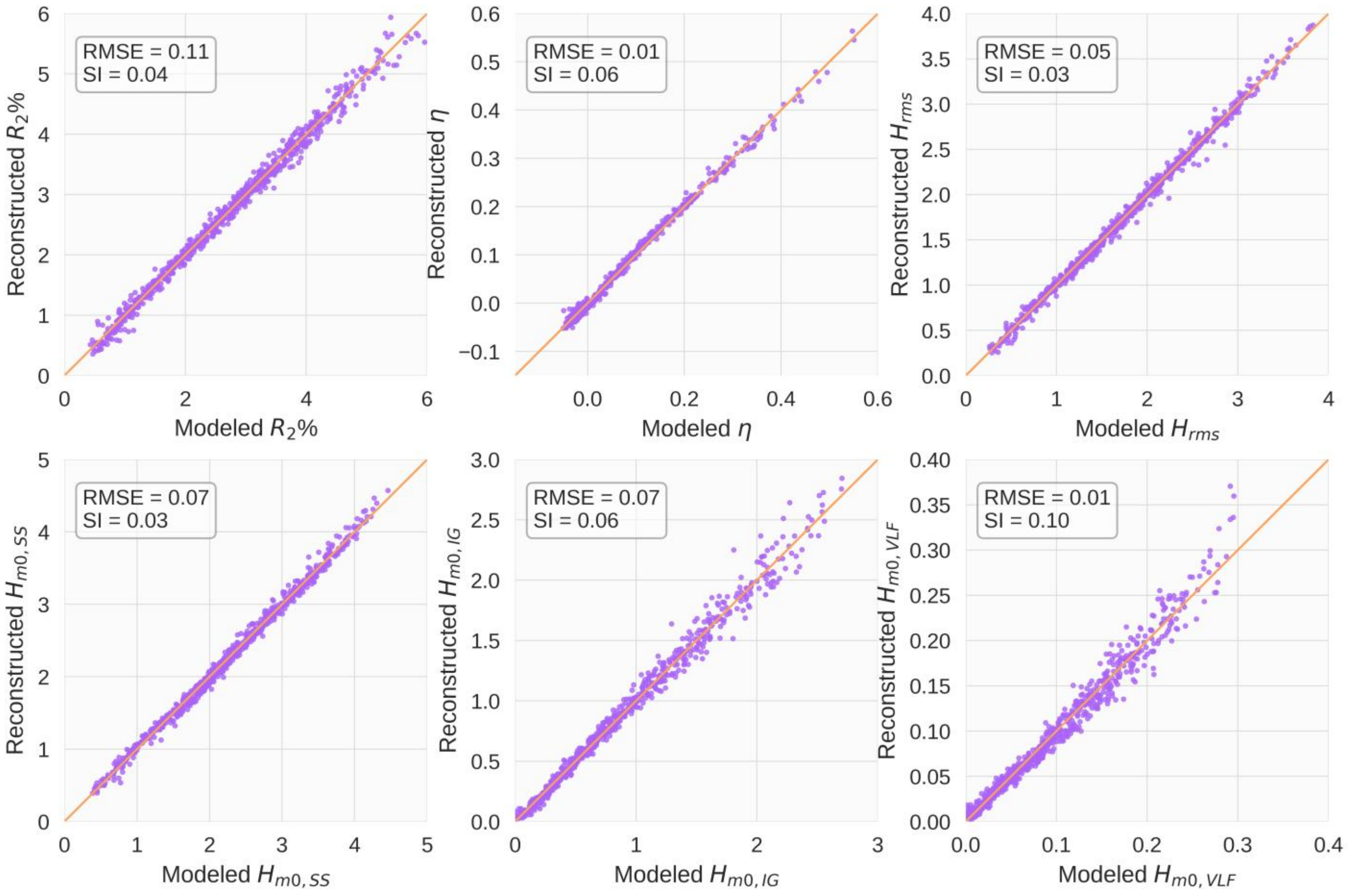


# HySwash. Numerical validation

**Determine minimum number of cases that minimize the error**

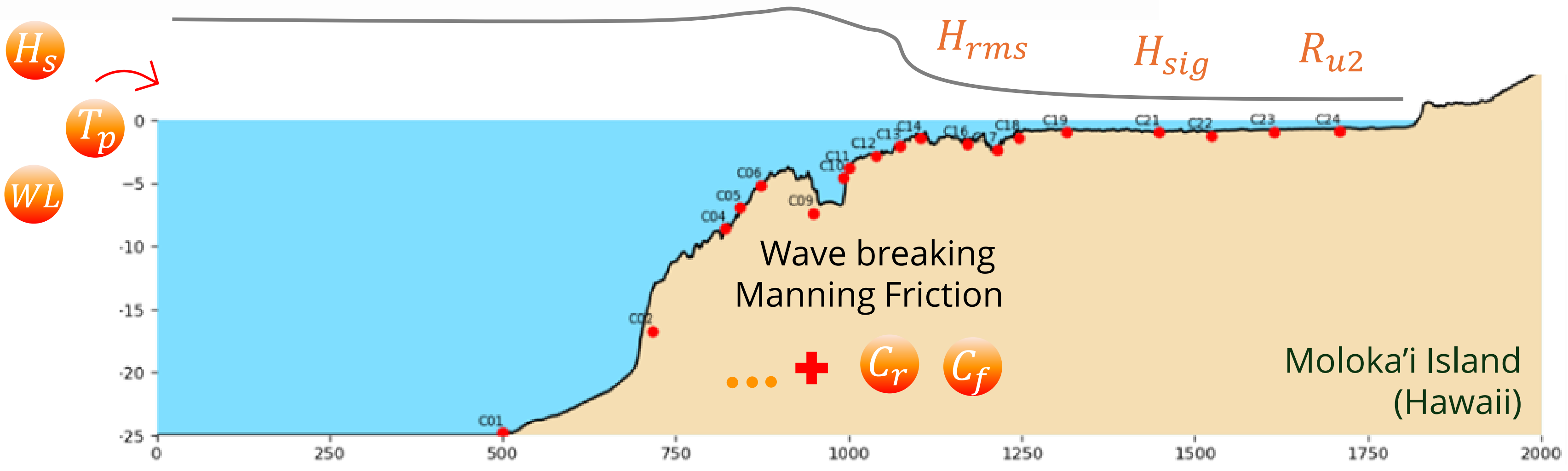
**K-fold cross-validation (k=5)**



# CHySwash

Automatic calibration method to find the optimal combination of model calibration parameters



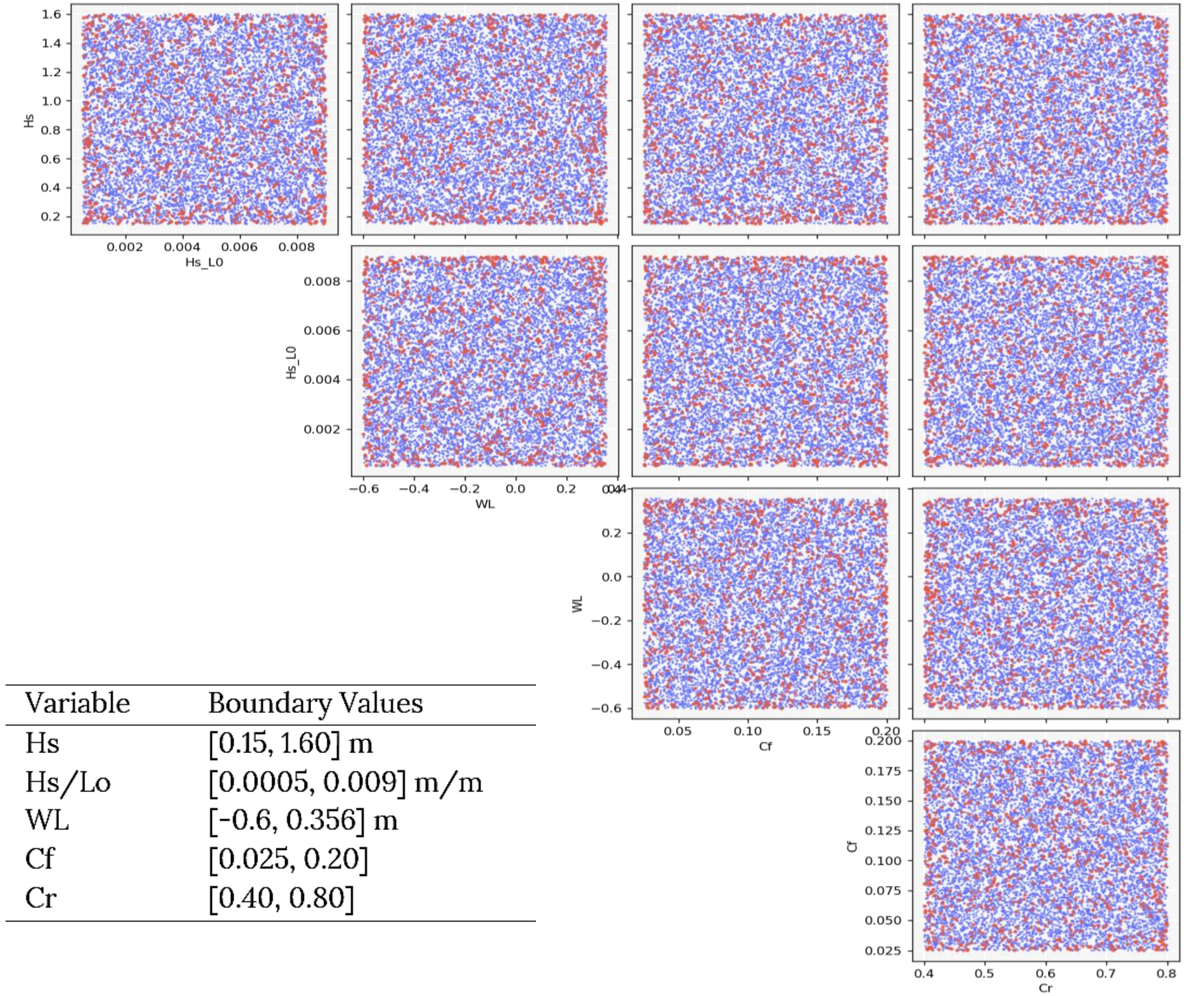

| | |
|---|---|
| Sampling | Latin Hypercube Sampling **(LHS)** |
| Selection | Maximum Dissimilarity Algorithm **(MDA)** |
| Numerical Model | **SWASH-1D** |
| Dimensionality Reduction | Principal Component Analsys **(PCA)** |
| Interpolation | Radial Basis Function **(RBF)** |
| Optimization algorithm | Shuffled Complex Evolution **(SCE)** |

$$J(C) = \frac{1}{m}\sum_{i=1}^{m}\left(h_c\left(x^{(i)}\right) - y^{(i)}\right)^2$$

# CHySwash

## LHS + MDA

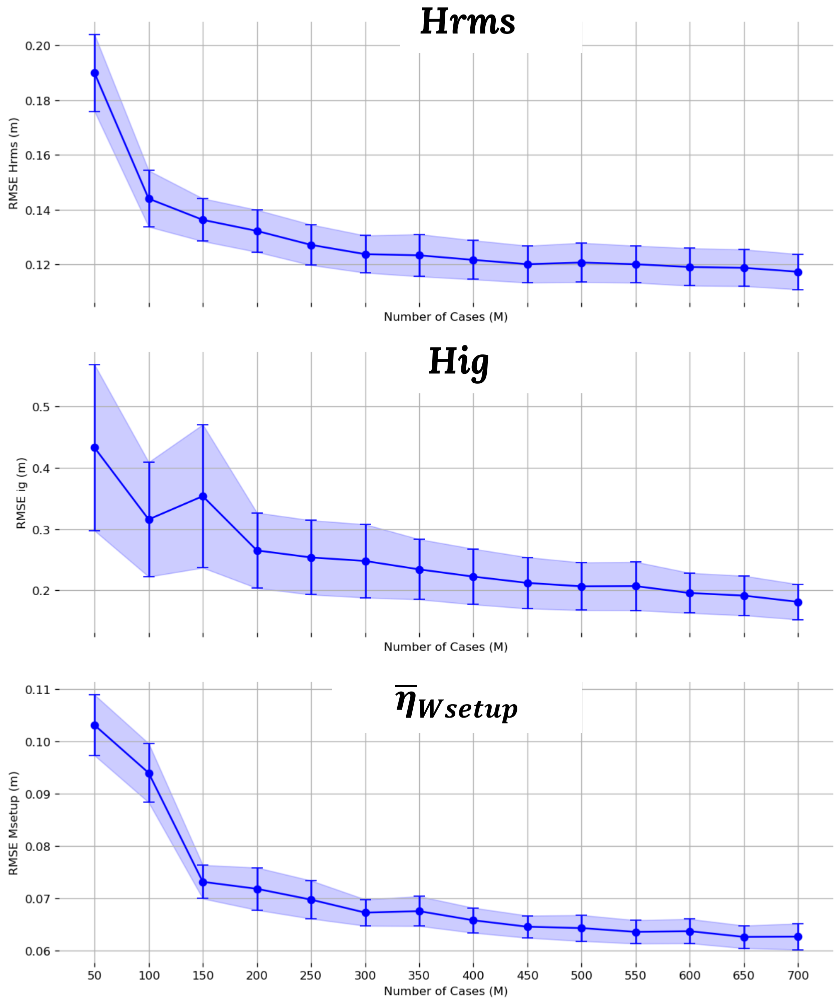
Candidate sampling size M = 700




| Variable | Boundary Values |
|---|---|
| Hs | [0.15, 1.60] m |
| Hs/Lo | [0.0005, 0.009] m/m |
| WL | [-0.6, 0.356] m |
| Cf | [0.025, 0.20] |
| Cr | [0.40, 0.80] |

## Numerical Validation

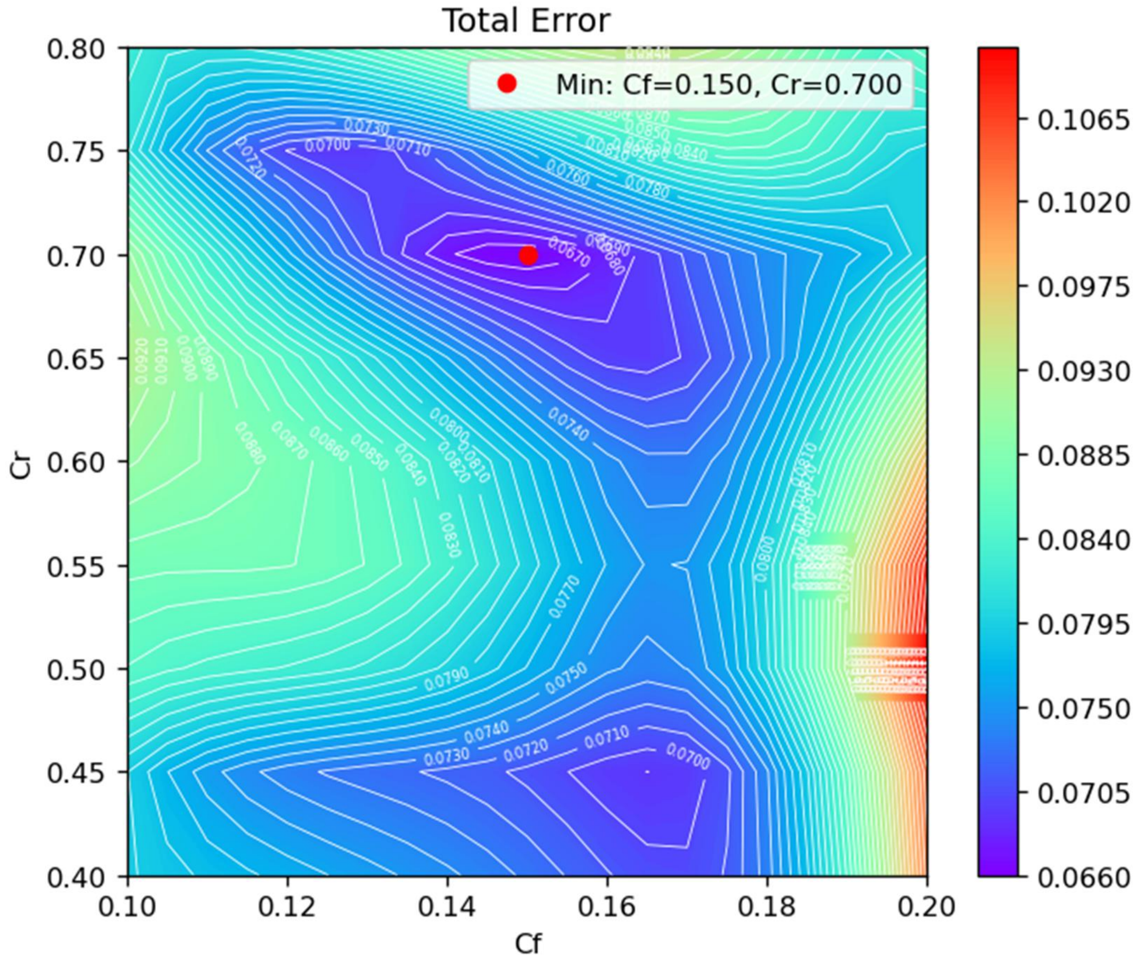
K-fold cross-validation (k=5)



# CHySwash. Results

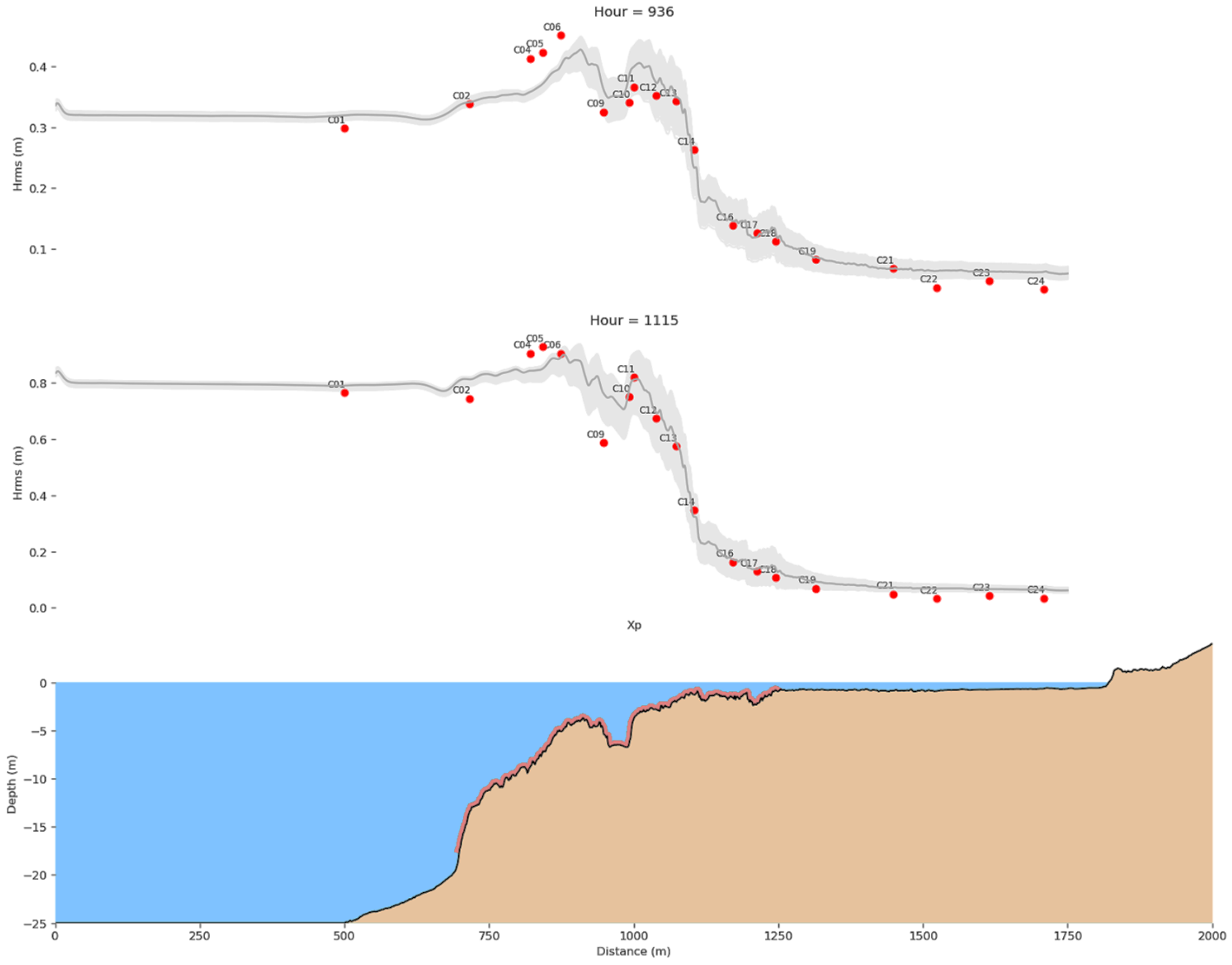
**Optimal combination of the calibration coefficients**

- **$Cf$=0.145 y $Cr$=0.708**
- RMSE 0.066m

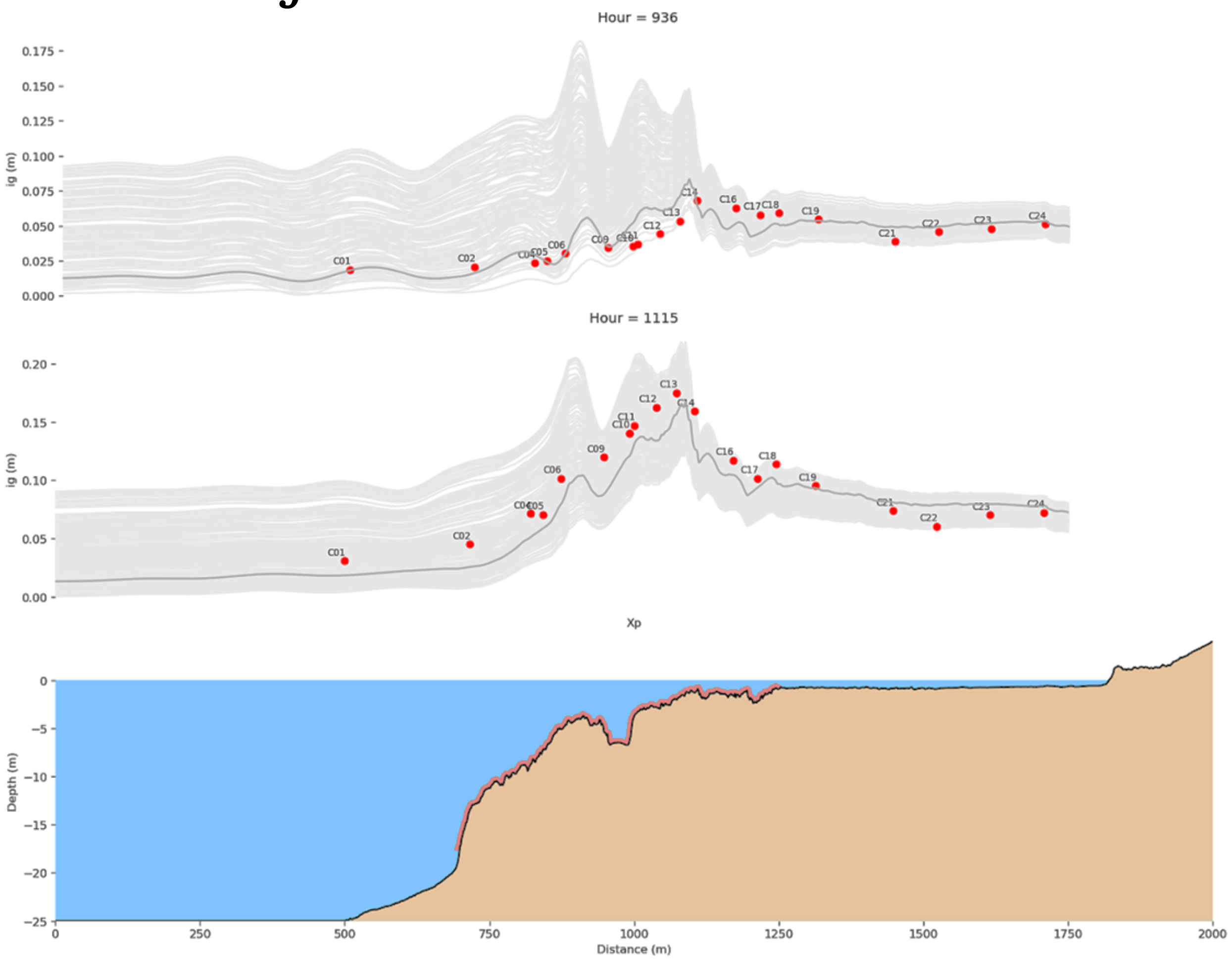


# CHySwash. Results

**_Hrms_**



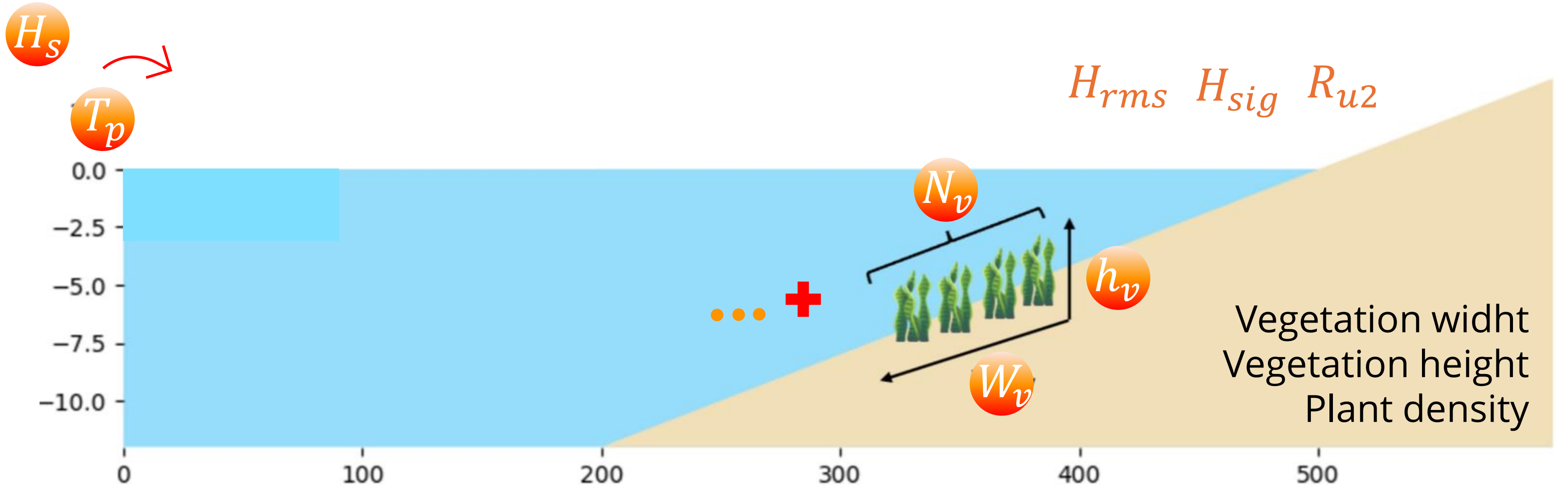

**_Hig_**



# HyVeggy

Assessment of nature-based solutions effectiveness for coastal protection

- ➢ e.g. how vegetation affects wave run-up

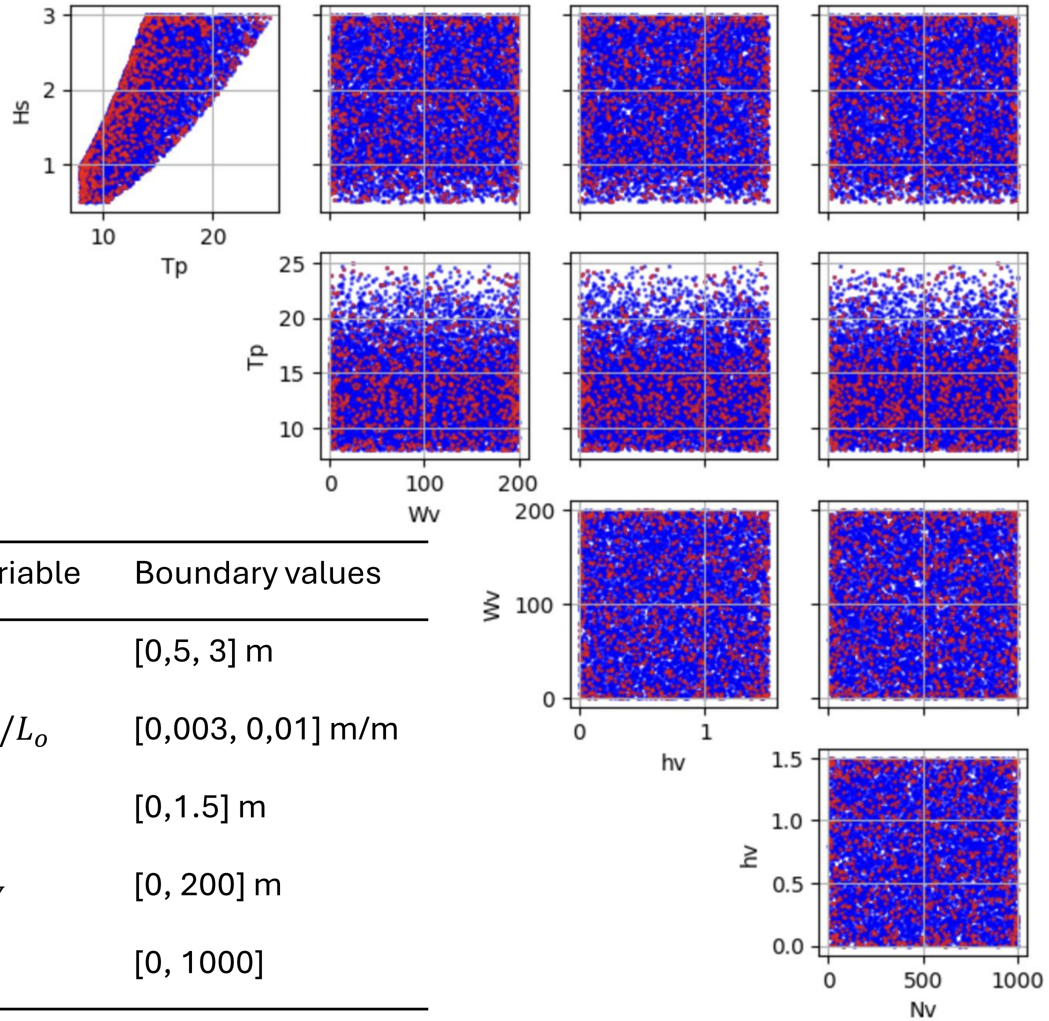



| | |
|---|---|
| Sampling | Latin Hypercube Sampling **(LHS)** |
| Selection | Maximum Dissimilarity Algorithm **(MDA)** |
| Numerical Model | **SWASH-1D** |
| Dimensionality Reduction | Principal Component Analsys **(PCA)** |
| Interpolation | Radial Basis Function **(RBF)** |

# HyVeggy

## LHS + MDA

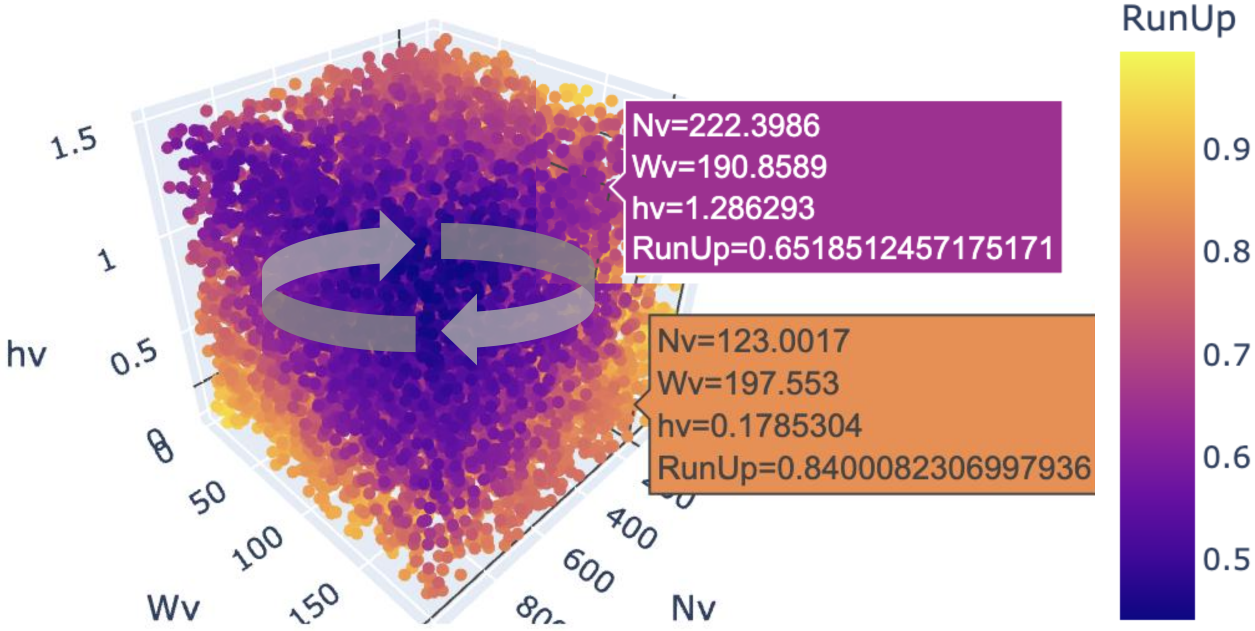
Candidate sampling size M = 1000



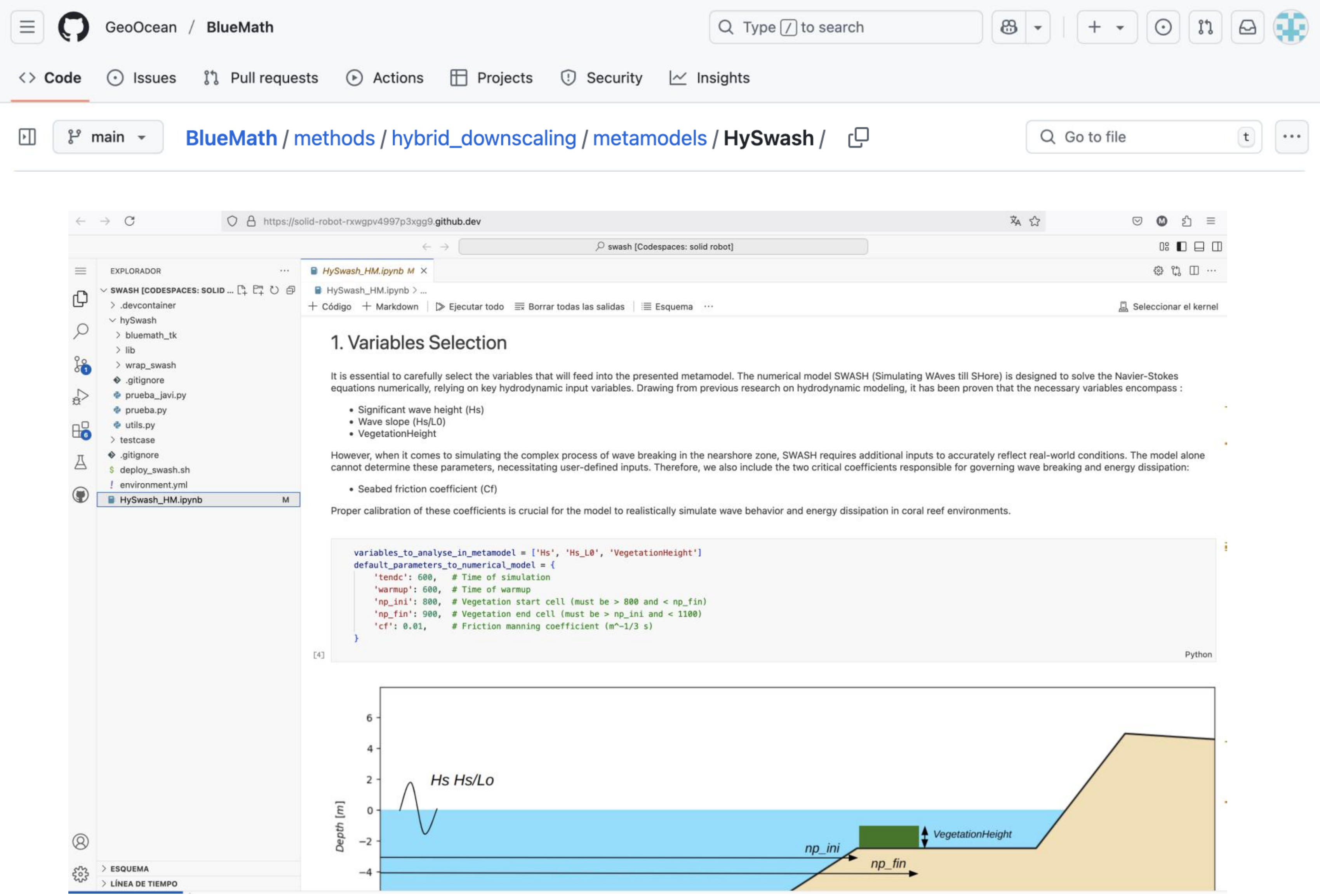

| Variable | Boundary values |
|---|---|
| $H_S$ | [0,5, 3] m |
| $H_S/L_o$ | [0,003, 0,01] m/m |
| $h_V$ | [0,1.5] m |
| $W_V$ | [0, 200] m |
| $N_V$ | [0, 1000] |

## Results

Wave run-up scatter plot
(e.g. Hs=1,5m: Hs/Lo=0,005)

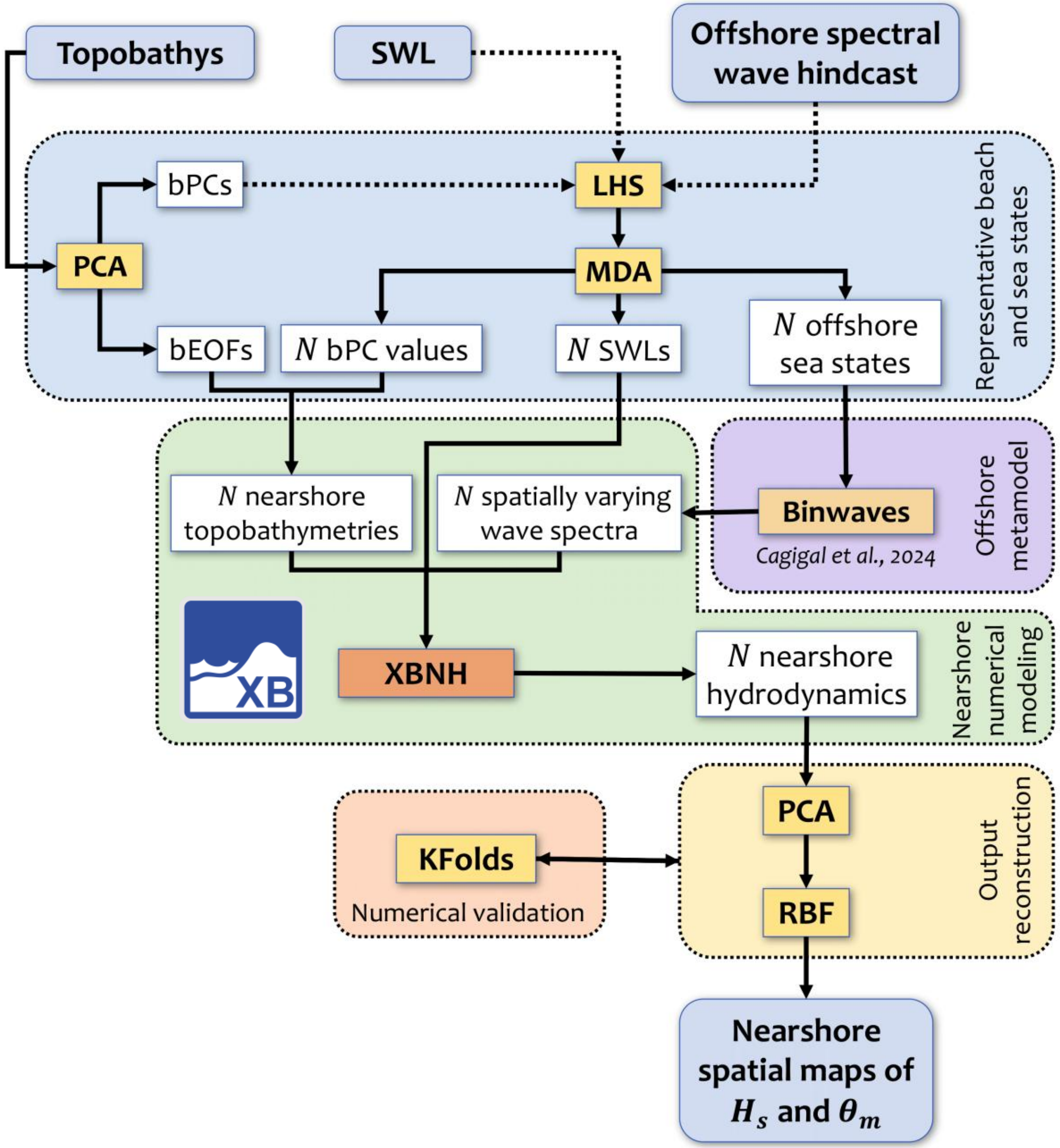


# HySwash. Cloud



# HyWaTHy

**HY**brid modeling of nearshore **WA**ves with varying ba**THY**s


- ✓ Propagation and dissipation of wave energy
- ✓ Bathymetric states

# Hybrid models

Universidad de Cantabria

Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

Contents lists available at ScienceDirect

**Ocean Engineering**

journal homepage: www.elsevier.com/locate/oceaneng

ELSEVIER

HySwash: A hybrid model for nearshore wave processes

Alba Ricondo *, Laura Cagigal, Beatriz Pérez-Díaz, Fernando J. Méndez

Contents lists available at ScienceDirect

**Coastal Engineering**

journal homepage: www.elsevier.com/locate/coastaleng

ELSEVIER

Introducing bimodal sea-states in a hybrid model for nearshore wave processes

Alba Ricondo *, Laura Cagigal, Beatriz Pérez-Díaz, Fernando J. Méndez

Contents lists available at ScienceDirect

**Coastal Engineering**

journal homepage: www.elsevier.com/locate/coastaleng

ELSEVIER

HyWaThy: Hybrid modeling of nearshore Waves with different baThymetric states

Manuel Zornoza-Aguado *, Beatriz Pérez-Díaz, Laura Cagigal, Sonia Castanedo, Fernando J. Méndez

BlueMath

- **Thursday**, 25th September 2025, **15:05-15:10** → **Poster Flash Presentation**: BlueMath: A Collaborative Open-Source Repository for Statistical Analysis and Fast, Efficient Hydrodynamic Emulators of Coastal Climate Hazards. **Laura Cagigal**

# Acknowledgments

PLATAFORMA WEB **BAHIALAB**: DATOS AMBIENTALES PARA UN TURISMO AZUL SOSTENIBLE EN ESTUARIOS (Financiado por la Comunidad Autónoma de Cantabria y por la Unión Europea Next GenerationEU/PRTR)

UNA HERRAMIENTA EFICIENTE HÍBRIDA PARA VALORAR EL EFECTO DE MEDIDAS DE ADAPTACIÓN AL CAMBIO CLIMÁTICO EN ESTUARIOS Y BAHÍA (**HyBay**) (PID2022-141181OB-I00 - MCIN/AEI/10.13039/501100011033/ FEDER, UE

Universidad de Cantabria

Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

GOBIERNO DE ESPAÑA MINISTERIO DE UNIVERSIDADES

Financiado por la Unión Europea NextGenerationEU

Plan de Recuperación, Transformación y Resiliencia

# Thank you!

Beatriz Pérez-Díaz (perezdb@unican.es)

# A Hybrid Modelling Framework for solving Nearshore Hydrodynamics

Beatriz Pérez-Díaz, Alba Ricondo, Laura Cagigal, Manuel Zornoza-Aguado, Valvanuz Fernandez-Quiruelas, Pablo Alonso-Alguacil, Fernando Méndez, Sonia Castanedo

4TH INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES, AND COASTAL HAZARDS
Incorporating the 18th International Waves Workshop

# Numerical modelling

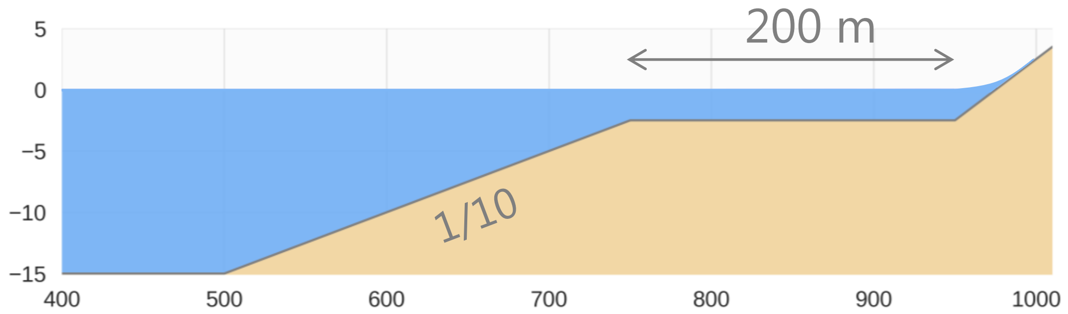
**Computational grid**
60 nodes per wavelength

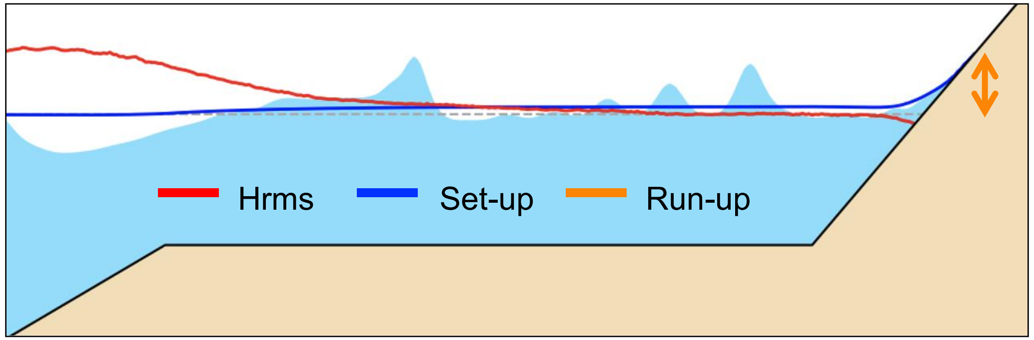
**Boundary conditions**
TMA spectra as Surface elevation
Weakly reflective W
Radiation E
Manning coefficient of 0.002

**Numerical parameters**
Non-hydrostatic 1D mode
2 vertical layers
4 hours of simulation
Automatic time integration (courant 0.1-0.5)

**Post-processed output quantities**
2% Run-up
Msetup
Hrms
Hss (1-25s), Hig (25-250s), Hvlf (250-1000s)

SWASH model (version 8.01) (Zijlema et al., 2011)



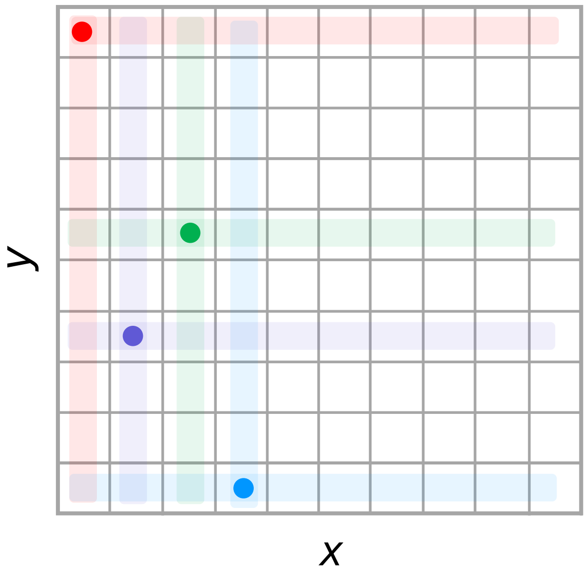
# Hydrodynamic forcing

**Latin Hypercube Sampling (LHS)**
**(Helton et al., 2005)**

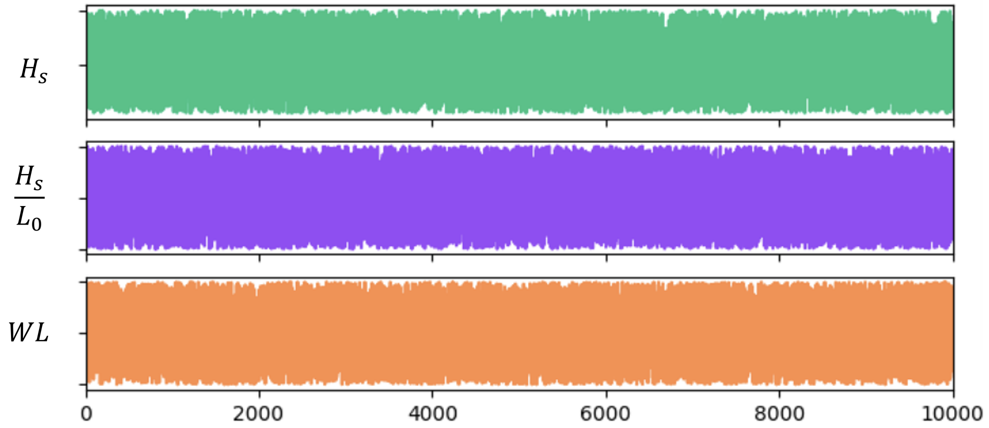
Considering unseen extreme scenarios

Synthetic Boundary Conditions

*2 dimensional LHS*

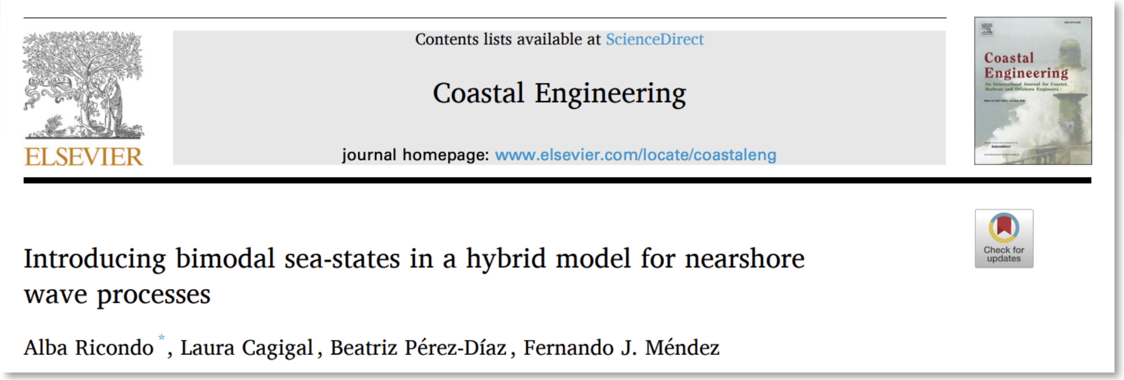



| Var | Range | |
|---|---|---|
| $H_s$ | 0.5 | 3 |
| $WL$ | -1 | 1 |
| $\frac{H_s}{L_0}$ | 0.005 | 0.5 |




**N = 10.000 combinations**

# HySwash. Bimodal


Contents lists available at ScienceDirect

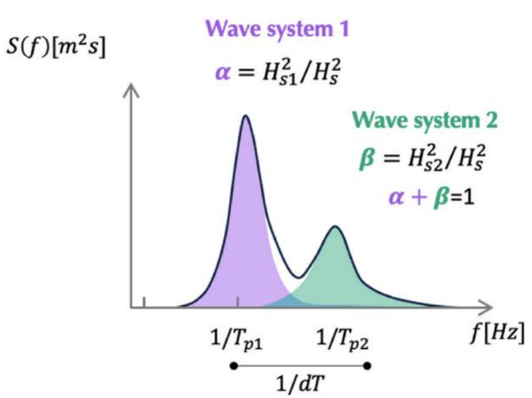
Coastal Engineering

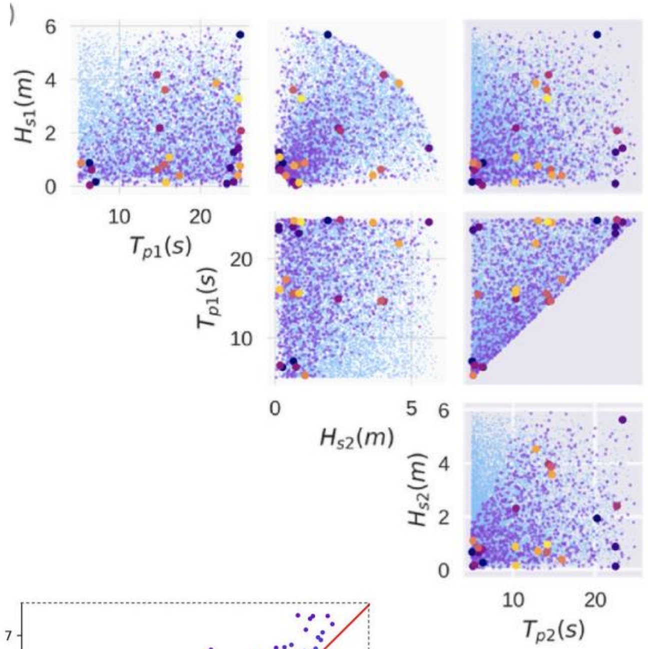
journal homepage: www.elsevier.com/locate/coastaleng

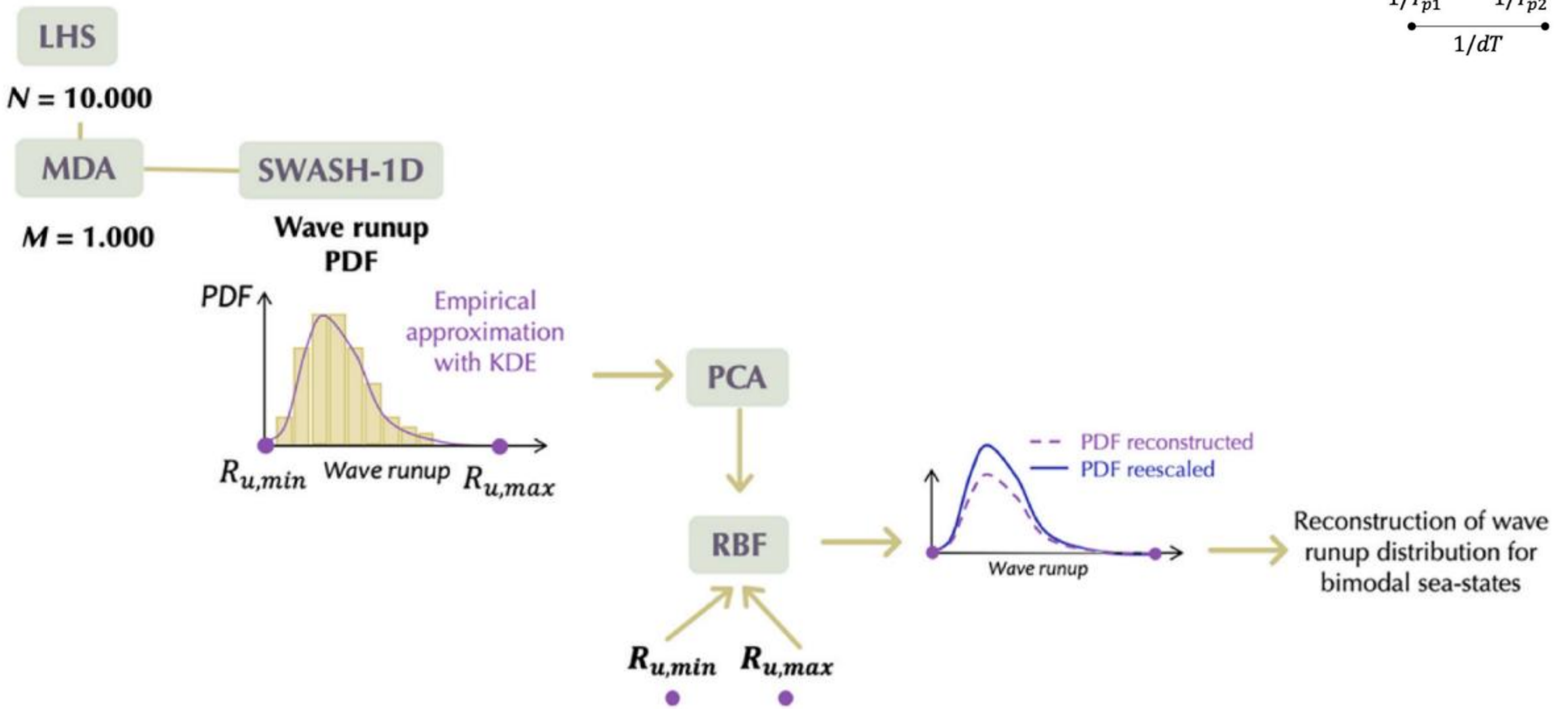
ELSEVIER

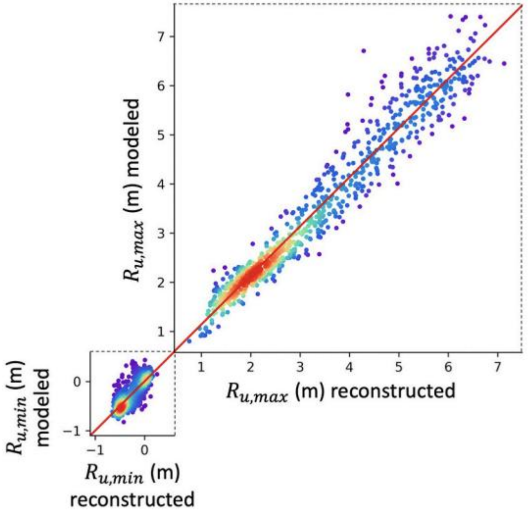
Introducing bimodal sea-states in a hybrid model for nearshore wave processes

Alba Ricondo *, Laura Cagigal, Beatriz Pérez-Díaz, Fernando J. Méndez



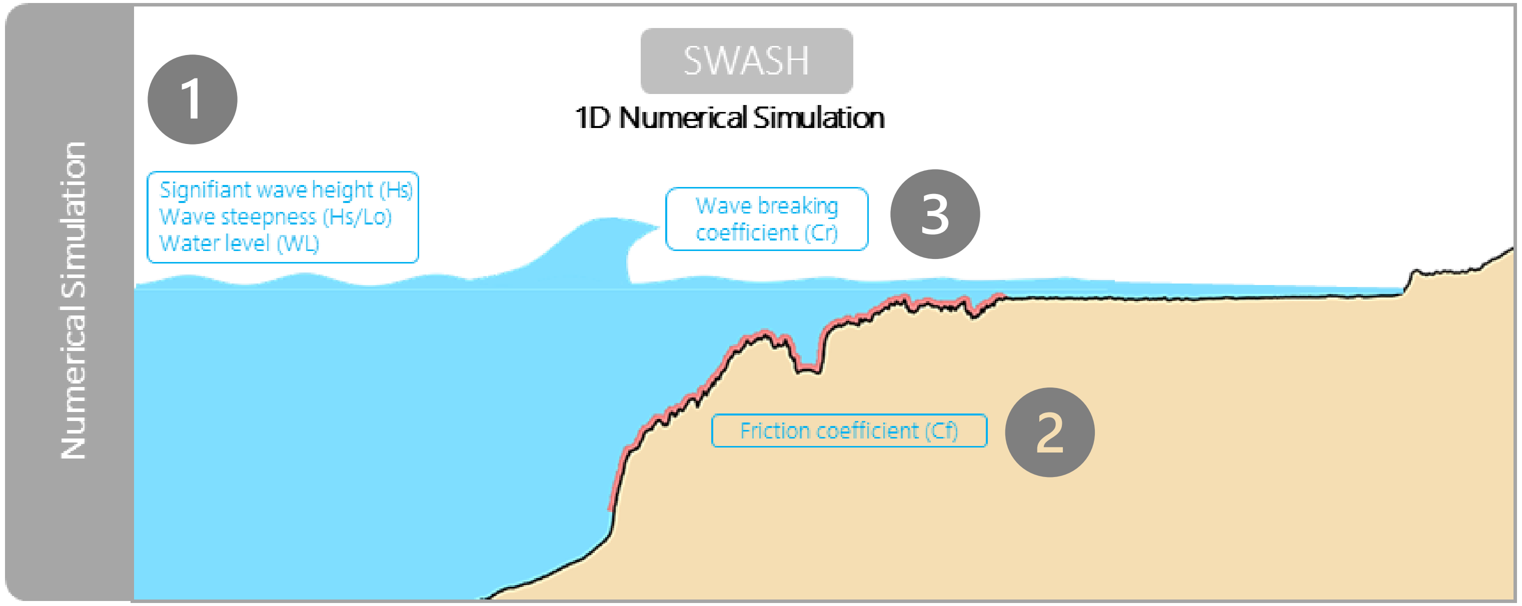
# CHySwash Methodology

## LIBRARY OF CASES

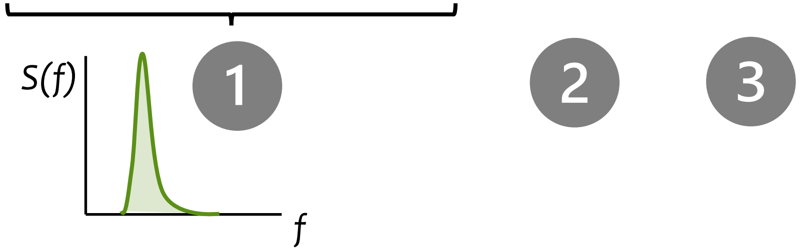
**700 numerical simulation with Swash model**

(version 8.01) (Zijlema et al., 2011)

- Horizontal discretization →60 nodes per wavelength
- Vertical discretization → 5 layers
- Hydraulic Boundary conditions → TMA spectra as surface elevation
- Bottom Friction →Manning of 0.002 in non-coral region
- Simulation Time →2 hours
- Output variables → $H_{rms}, H_{ig}, \bar{\eta}$




| | Hs | Hs_L0 | WL | Cf | Cr |
|---|---|---|---|---|---|
| 0 | 1.599905 | 0.001230 | -0.539943 | 0.118384 | 0.754619 |
| 1 | 0.168547 | 0.008677 | 0.341169 | 0.161420 | 0.407984 |
| 2 | 1.478708 | 0.008897 | 0.333209 | 0.034138 | 0.715611 |
| 3 | 0.172319 | 0.000697 | 0.328727 | 0.120217 | 0.796866 |
| 4 | 0.342142 | 0.008833 | -0.498110 | 0.198403 | 0.793661 |
| ... | ... | ... | ... | ... | ... |
| 695 | 0.783637 | 0.006686 | -0.205266 | 0.030537 | 0.794249 |
| 696 | 1.047265 | 0.004955 | 0.276082 | 0.194612 | 0.571215 |
| 697 | 0.200190 | 0.002673 | 0.132519 | 0.134621 | 0.415133 |
| 698 | 0.214312 | 0.002393 | -0.589623 | 0.091099 | 0.675439 |
| 699 | 0.625319 | 0.008919 | -0.404267 | 0.078414 | 0.544013 |



| Case | Simulation time (sec) | Horizontal Mesh Resolution: number of nodes per wavelength | Number of vertical layers in the numerical model | Case resolution time (sec) | Graph Color |
|---|---|---|---|---|---|
| 1 | 7200 | 30 | 2 | 182.36 | Blue |
| 2 | 7200 | 60 | 2 | 520.37 | Yellow |
| 3 | 7200 | 30 | 3 | 280.08 | Green |
| 4 | 7200 | 60 | 3 | 794.78 | Red |
| 5 | 7200 | 30 | 5 | 441.92 | Purple |
| 6 | 7200 | 60 | 5 | 1374.43 | Brown |

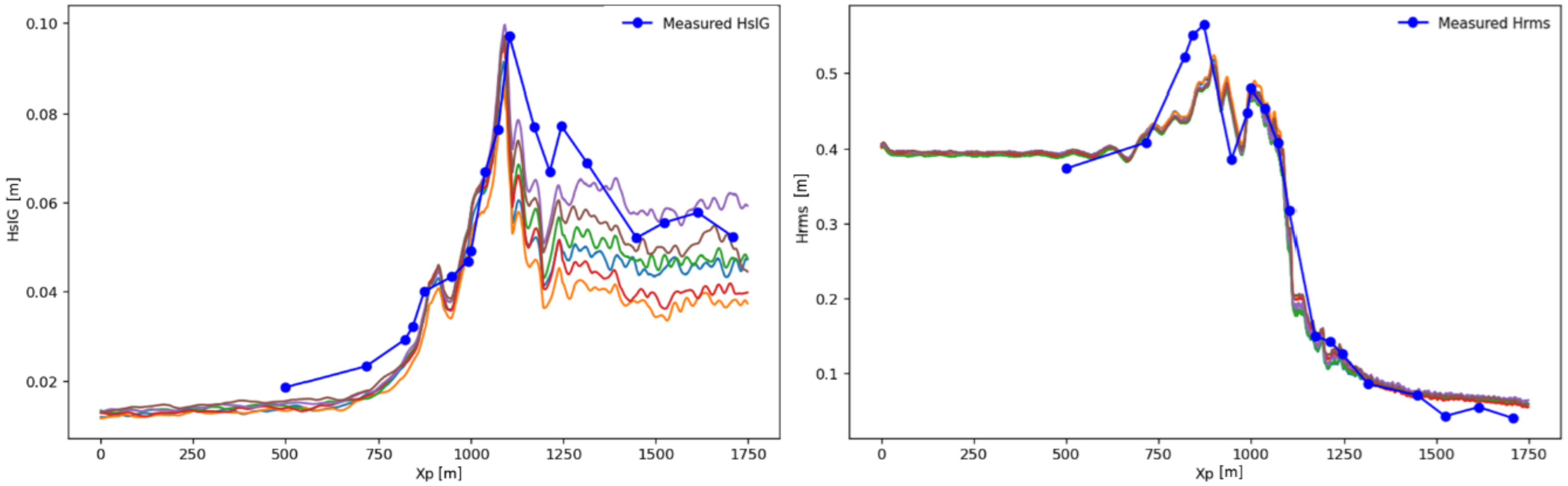


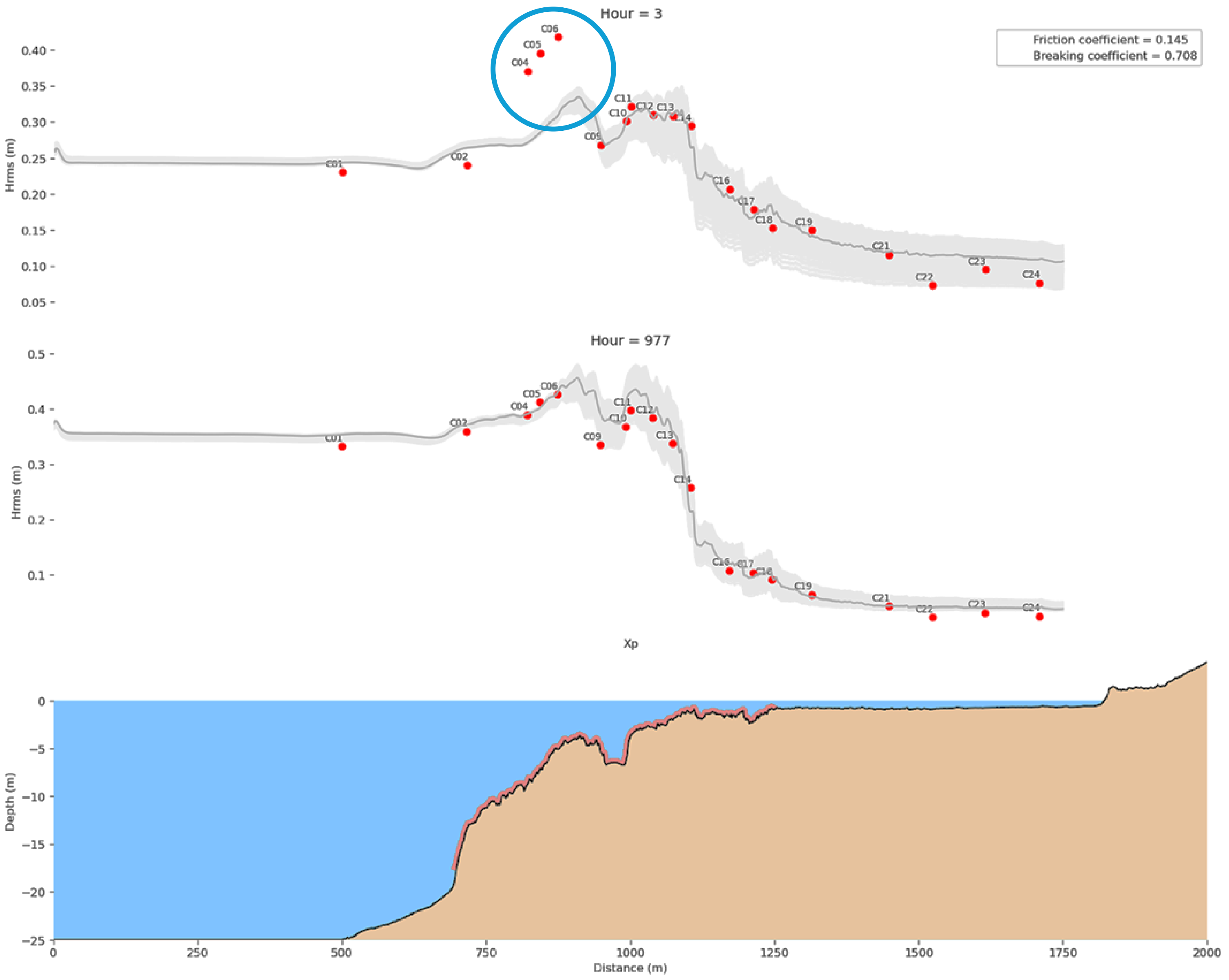

Table 3. Summary of simulation parameters and their corresponding outputs. Each case varies by simulation time, horizontal mesh resolution (nodes per wavelength), and the number of vertical layers in the numerical model. Graph colors represent different parameter combinations. (Source: Created by the author).

# CHySwash Results

**Análisis bidimensional**

**Zona problemática.** Cresta del arrecife
Sensores C04, C05 y C06

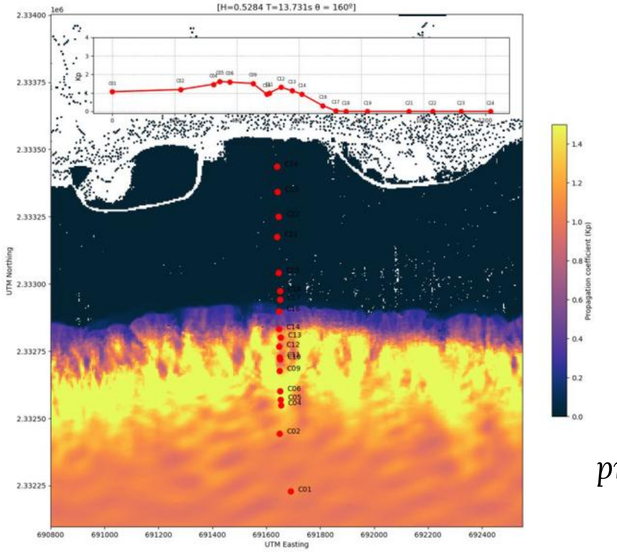
- **Efectos transversales.** Modelo unidimensional que no toma en cuenta los efectos transversales y la concentración de energía de las olas.
- **Oblicuidad de las olas.** Falta de información sobre la dirección de las olas, lo que puede ocasionar variaciones significativas en las alturas de las olas medidas in situ.



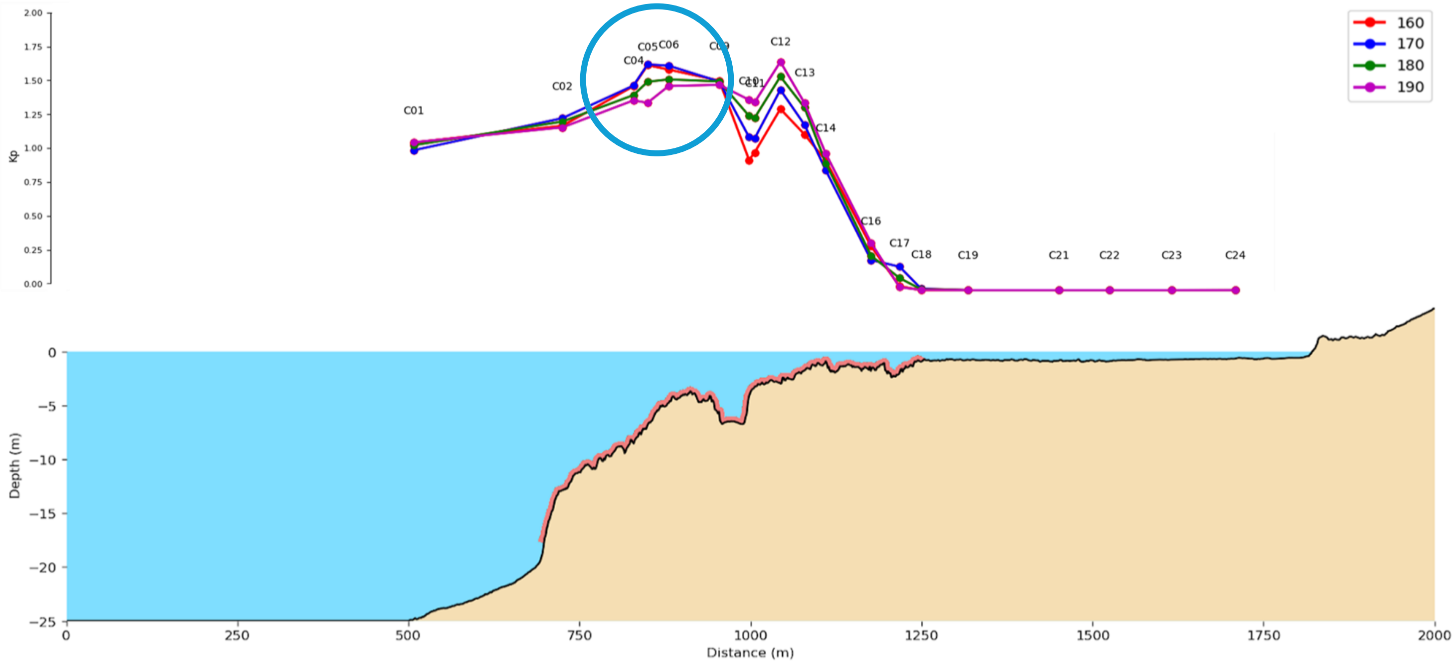
# CHySwash Results

**Análisis bidimensional**

**Modelo Xbeach nonh**




*Evolución del coeficiente de propagación de las olas Kp a lo largo del transecto.*



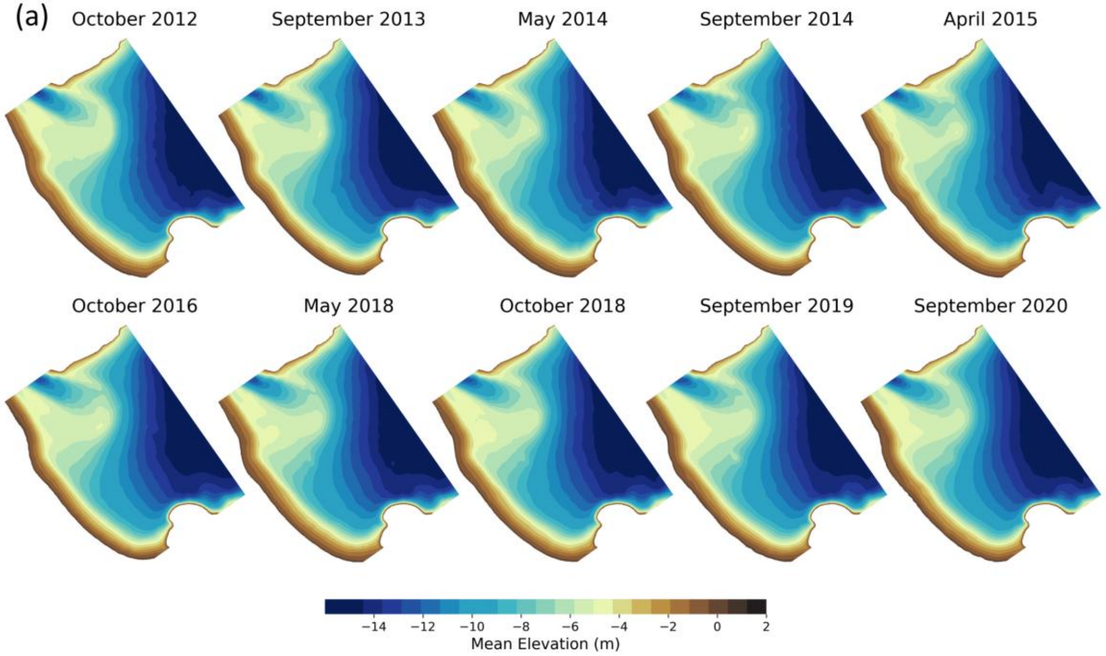

Coeficiente de propagación del oleaje ($Kp = Hrms/Hrms0$) para diferentes direcciones (variando de 160º a 190º).

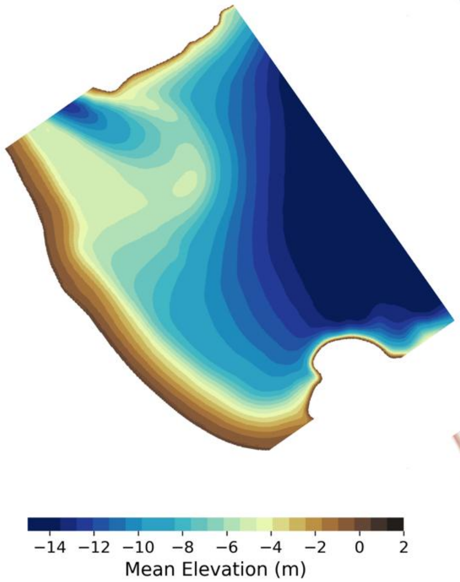
**En la cresta el factor *Kp* se amplifica para direcciones de las olas inferiores a 180°**

- Falta de información sobre la **dirección** de las olas en las condiciones de contorno.
- **Errores** de medición y **precisión** de los sensores.
- **Limitaciones metodológicas** del modelo de perfil que no considera los efectos transversales.

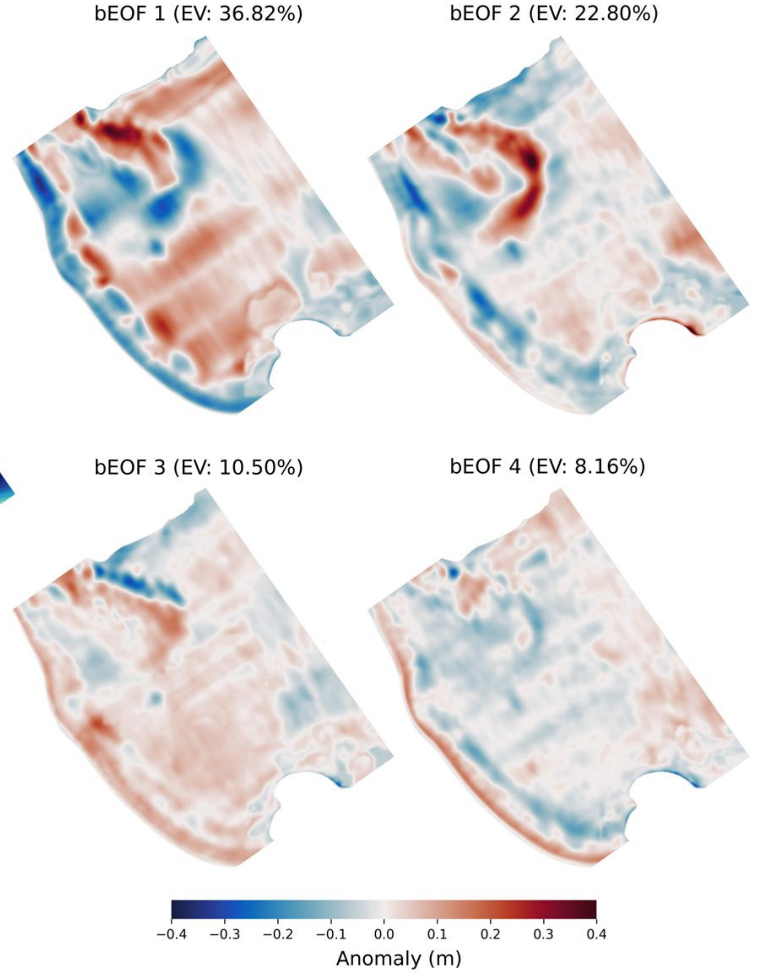
## Representative bathymetry states through PCA

$$z(x;t) = \overline{z}(x) + \sum_{i=1}^{B} bEOF_i(x) \cdot bPC_i\,(t)$$




80% explained variance

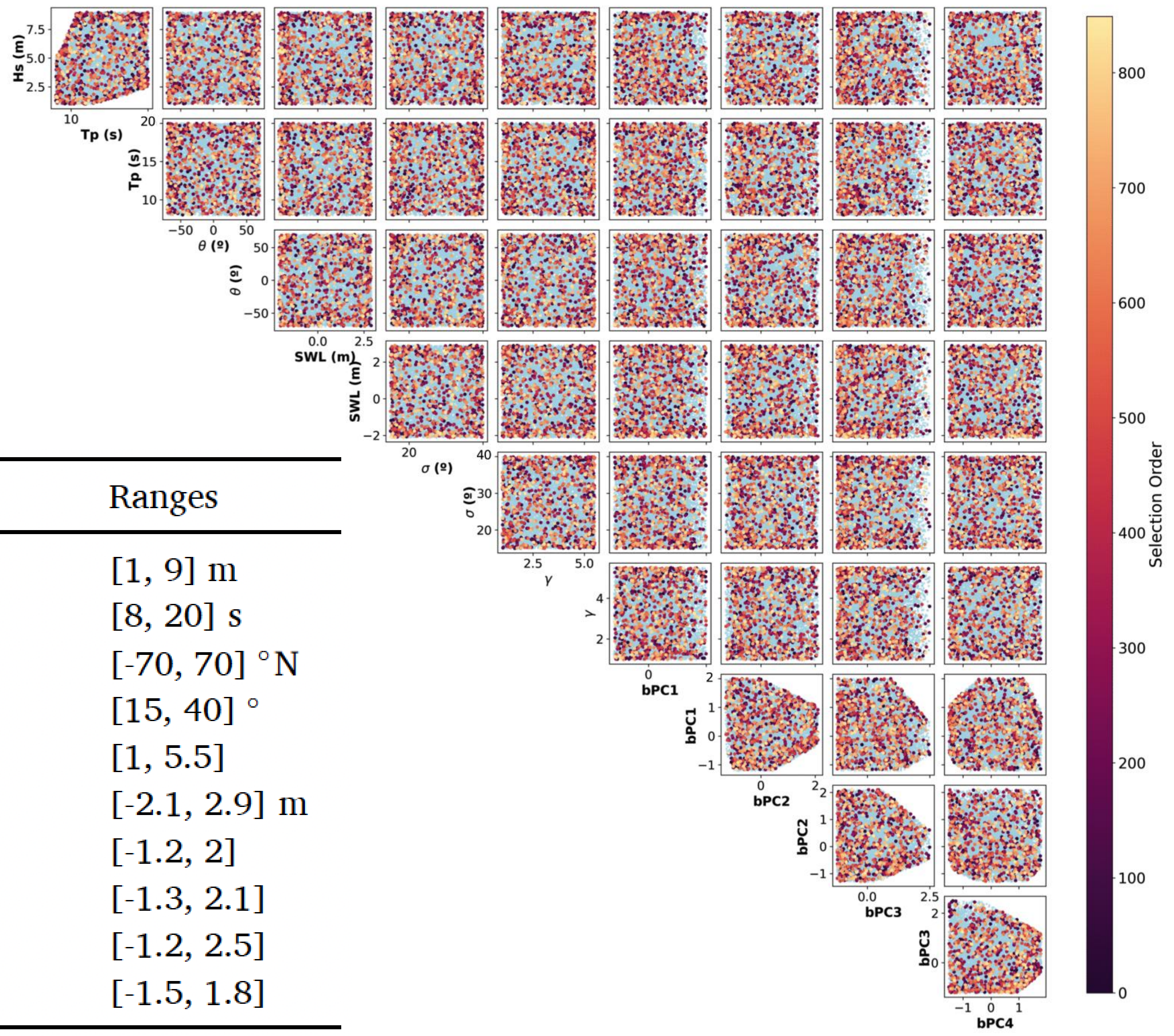



DATA: 10 nearshore topobathymetries ($\Delta x$ =10m, z=25m) from CEDEX

# HyWatHy

## LHS + MDA

Candidate sampling size M = 850




| Parameter | Symbol | Ranges |
|---|---|---|
| Offshore significant wave height | $H_s$ | [1, 9] m |
| Peak wave period | $T_P$ | [8, 20] s |
| Offshore mean wave direction | $\theta_m$ | [-70, 70] °N |
| Wave directional spreading | $\sigma$ | [15, 40] ° |
| JONSWAP peak enhancement factor | $\gamma$ | [1, 5.5] |
| Still water level | $\eta_{SWL}$ | [-2.1, 2.9] m |
| Topobathymetry first principal component | $bPC1$ | [-1.2, 2] |
| Topobathymetry second principal component | $bPC2$ | [-1.3, 2.1] |
| Topobathymetry third principal component | $bPC3$ | [-1.2, 2.5] |
| Topobathymetry fourth principal component | $bPC4$ | [-1.5, 1.8] |

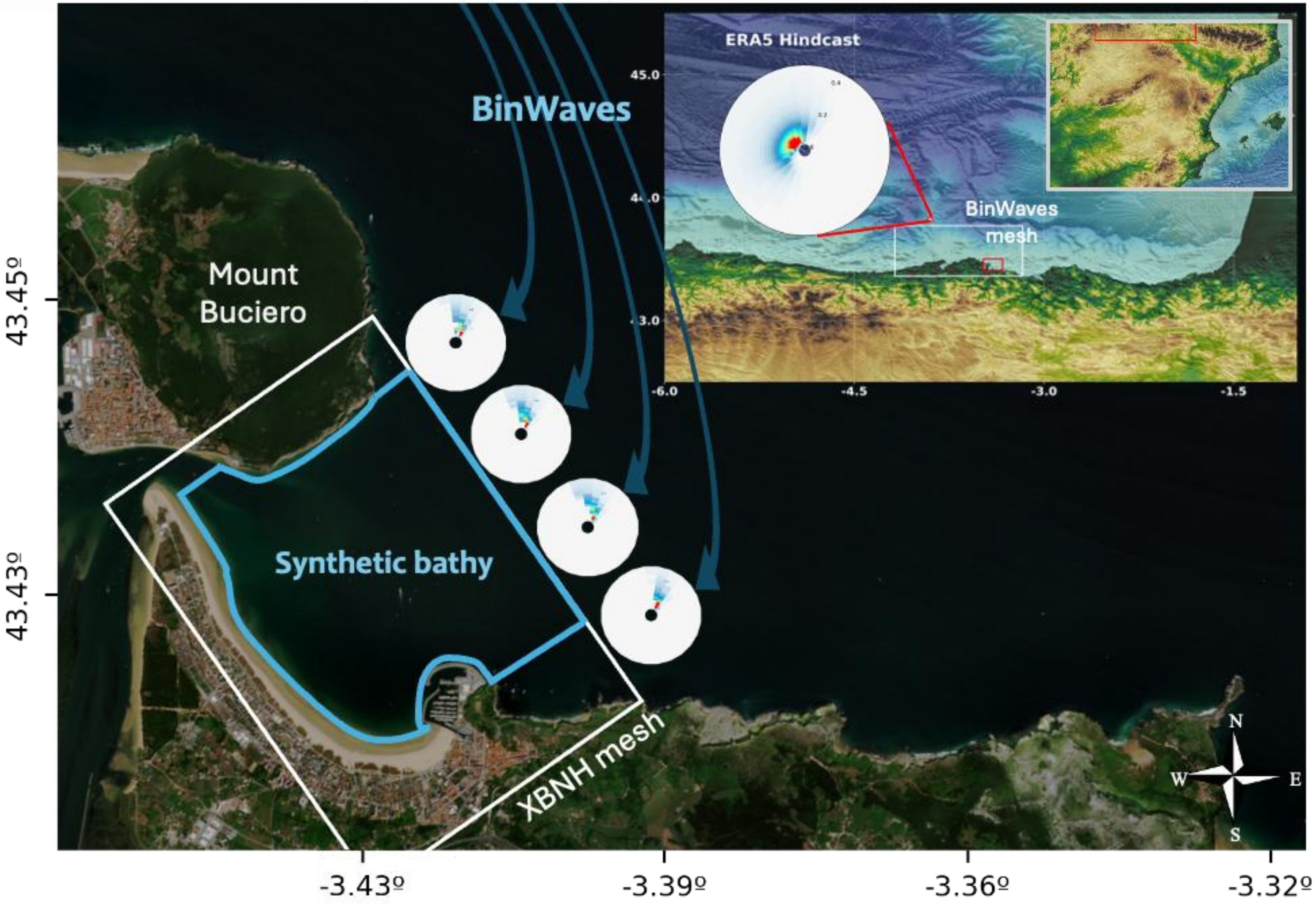
# HyWatHy

## Numerical Modelling (M = 850 cases)

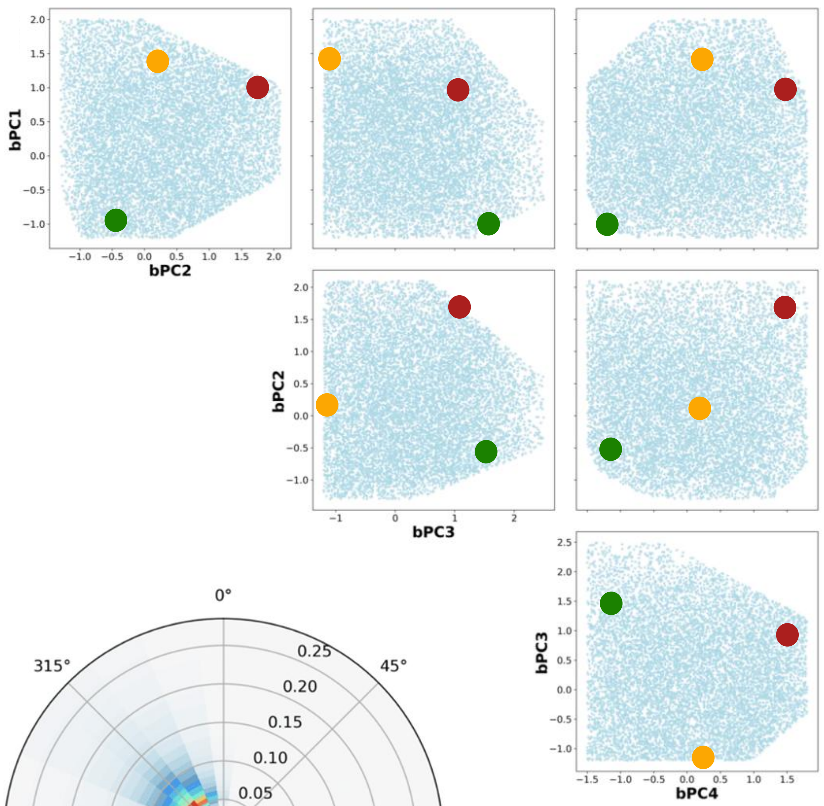
Roelvink et al., 2018
de Ridder et al., 2021

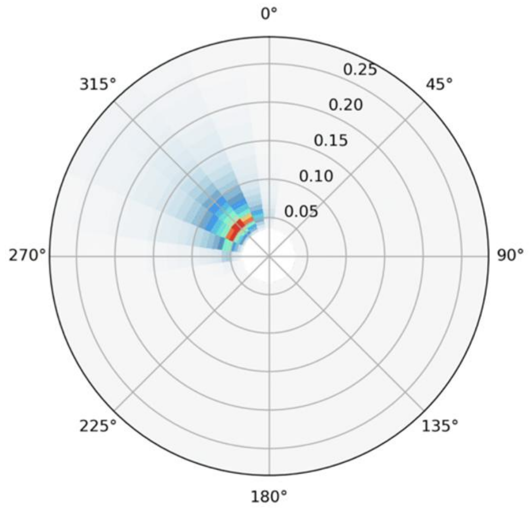
BinWaves

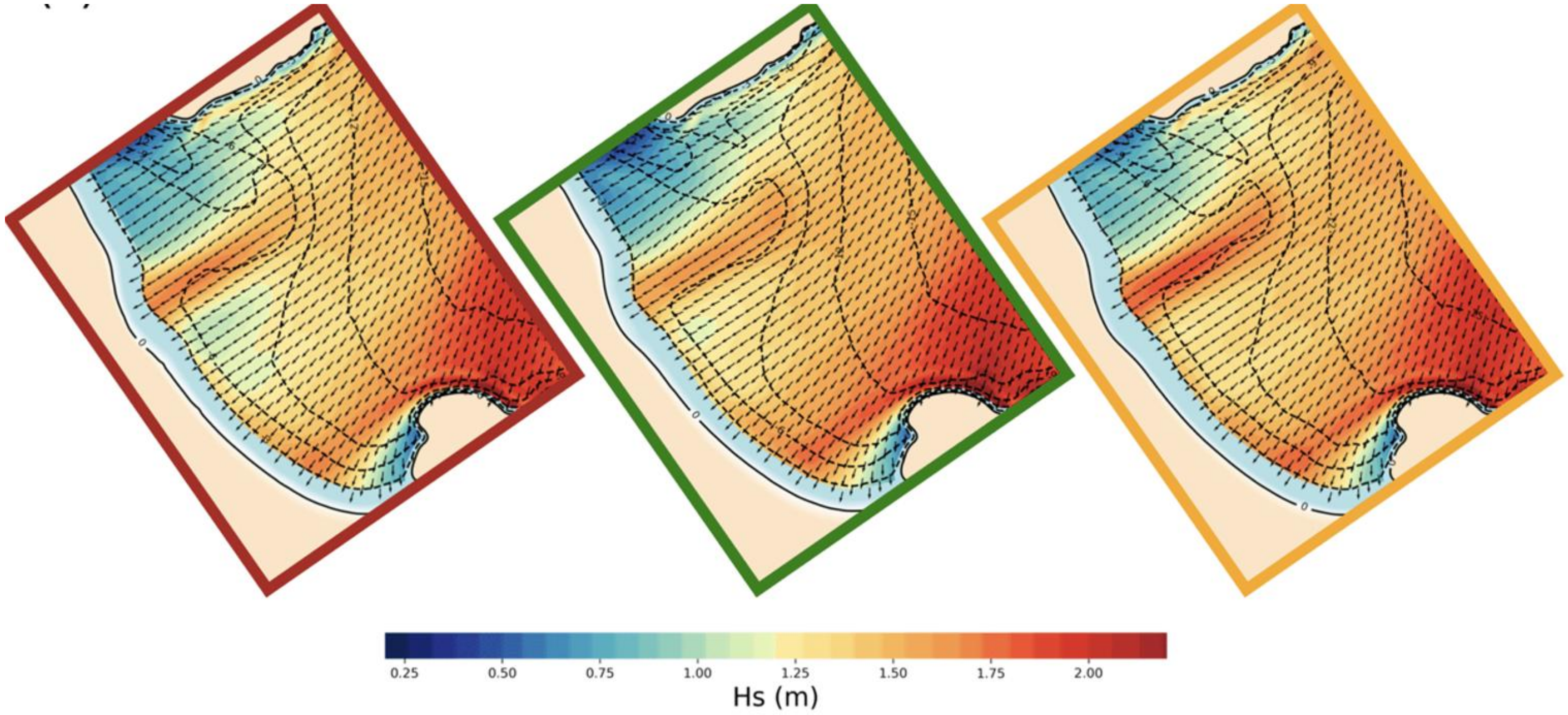
Cagigal et al., 2024



# HyWatHy. Results



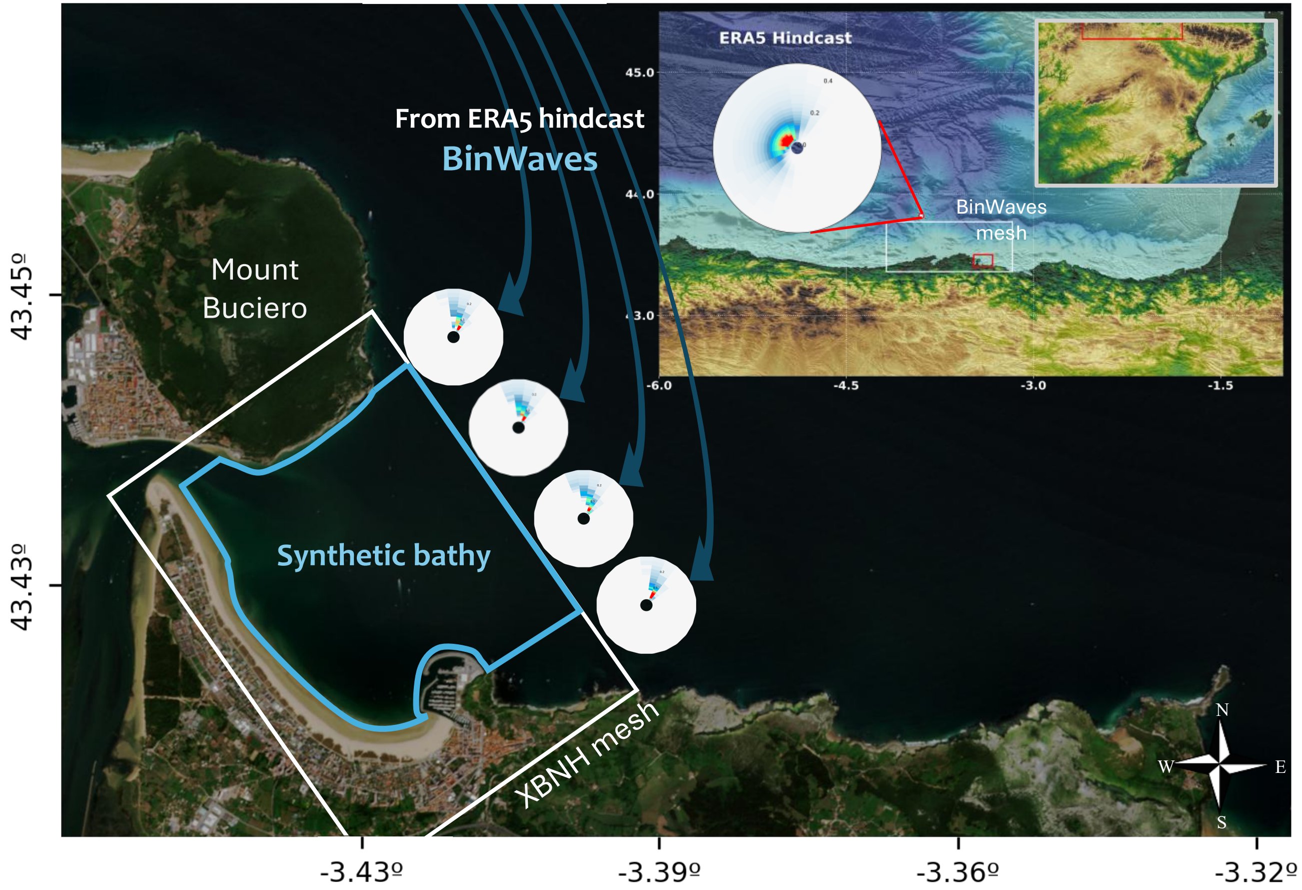



# Nearshore numerical modeling: XBeach NH

## *Numerical simulations (850 cases)*

*Roelvink et al., 2018*
*de Ridder et al., 2021*

- *Non hydrostatic* mode, 2DH (*phase resolving*)
- Structured rectangular grid ($\Delta x$= 5m)
- $f_w = 0.03$ (sand bottoms)
- No sediment transport
- 30 minutes (10min warmup)




**850 cases**

*$\{H_S, T_P, \theta_m, \sigma, \gamma$, SWL, bPC1, bPC2, bPC3, bPC4$\}$*

Cluster GeoOcean
5 x 48 cores (512GB RAM)


250 cases in parallel, 2 days 18h

**850 spatial fields**

$\{H_S, \theta_m\}$

# Offshore metamodel: BinWaves

(Cagigal et al., 2024)

Ocean Modelling

Volume 189, June 2024, 102346

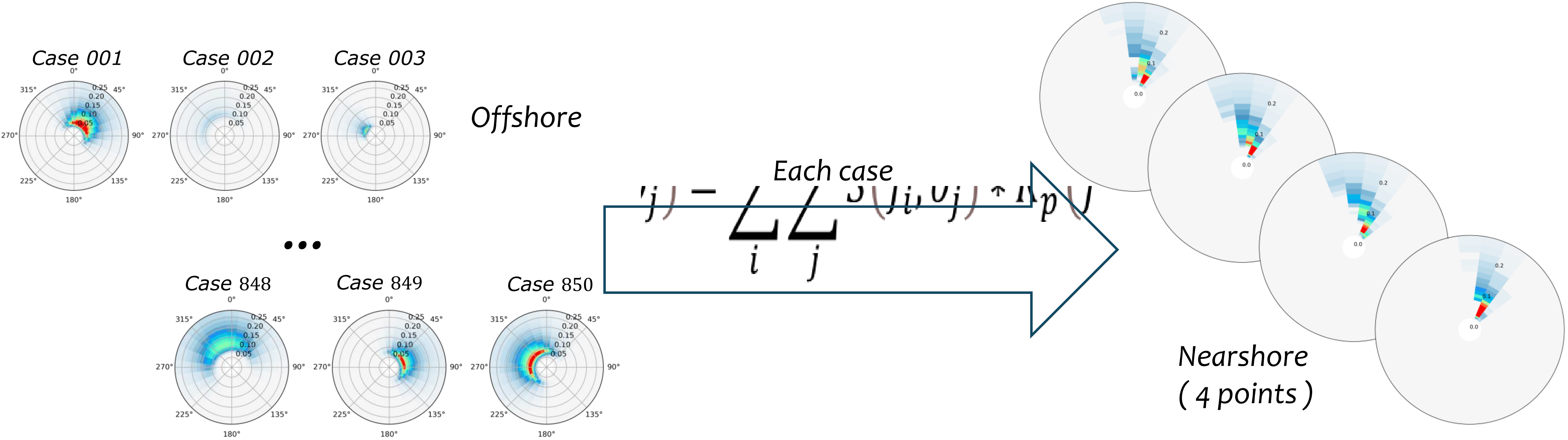
BinWaves: An additive hybrid method to downscale directional wave spectra to nearshore areas

Laura Cagigal [a], Fernando J. Méndez [a], Alba Ricondo [a], David Gutiérrez-Barceló [b], Cyprien Bosserelle [c], Ron Hoeke [d]

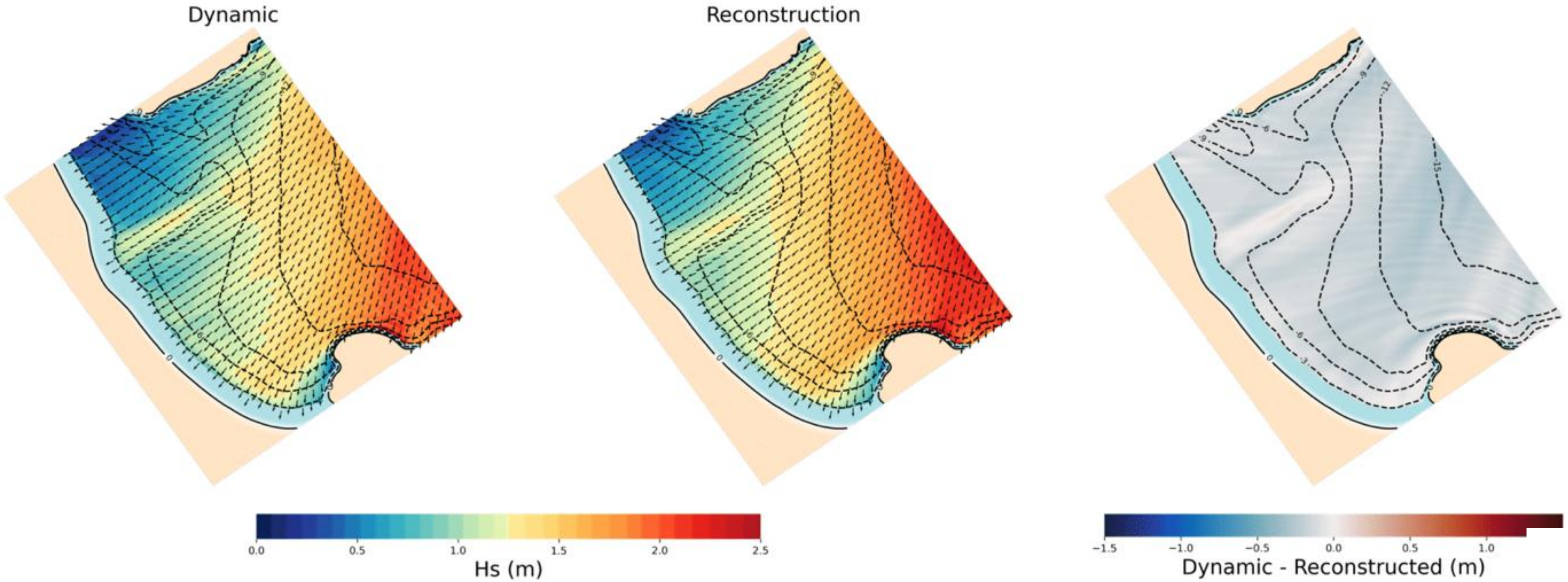
## Hybrid additive method to propagate full directional wave spectra to nearshore locations

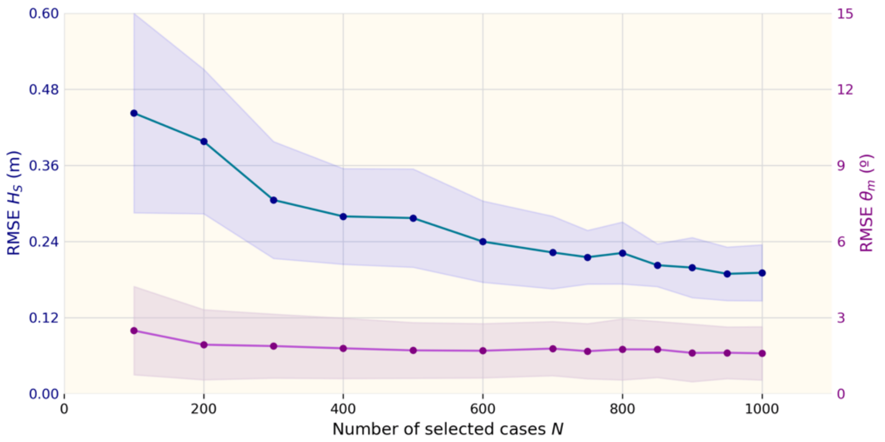
(Deep waters → non-linear interactions neglected)

1. Wave spectrum disaggregation (696 bins).
2. Propagation of monochromatic wave systems ($H_s = 1m$)
3. Obtention of propagation coefficients for each case ($K_p$).
4. Reconstruction of the sea state (linear sum)



# HyWatHy. Numerical validation



# Efficiency

Universidad de Cantabria

Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

Ubuntu (x86-64), using up to eight 3 GHz Intel i7-9700 processors and 32 GB of RAM

## CHySwash vs Classical calibration method

Forget expensive long dynamic simulations
Unlimited exploration of calibration coefficients
CHySwash library → 10 days
Optimal combinations (SCE) → seconds

**Efficiency**

Testing different **Climate Change scenarios**
Testing **adaptation and mitigation strategies** (nature-based solution, shore protection structures)

# Reconstruction

Ubuntu (x86-64), using
up to eight 3 GHz Intel i7-9700
processors and 32 GB of RAM

**Metamodel construction (M=1000 cases)**

9 minutes / simulation = 5 days

**Metamodel interpolation (40-year historical hindcast)**

5 minutes

**Efficiency**

Testing **adaptation and mitigation strategies** (nature-based solution, shore protection structures)

# HyBeat methodology