A New Framework for Correcting and Reconstructing High-Resolution CMIP6 GCM-based Directional Wave Spectra

Gabriel Bellido[1], Laura Cagigal[1], Fernando J. Méndez [1]

1 Geomatics and Ocean Engineering Group, Universidad de Cantabria, Santander, Spain.

Motivation

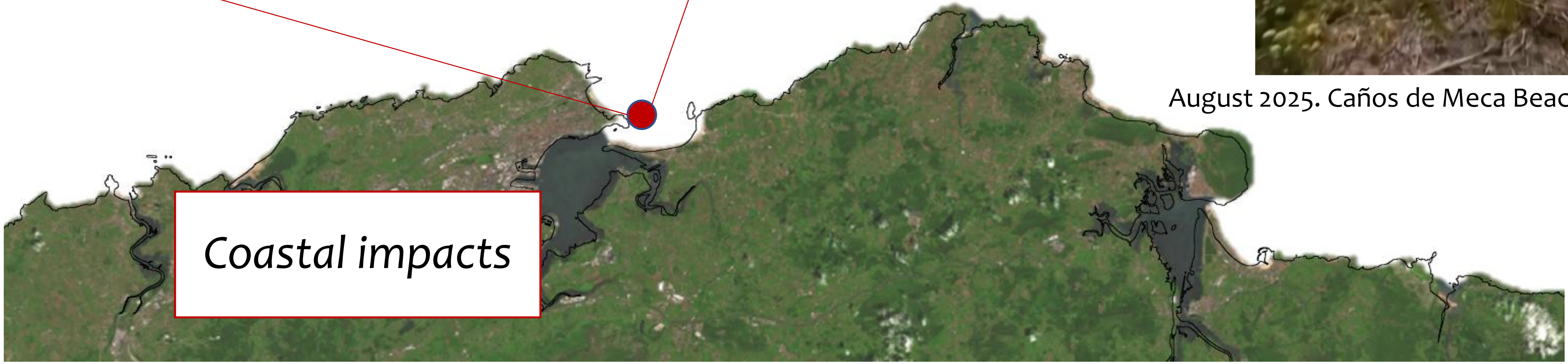
UC | Universidad de Cantabria

Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

¿How coastal dynamics will change under future climate scenarios?

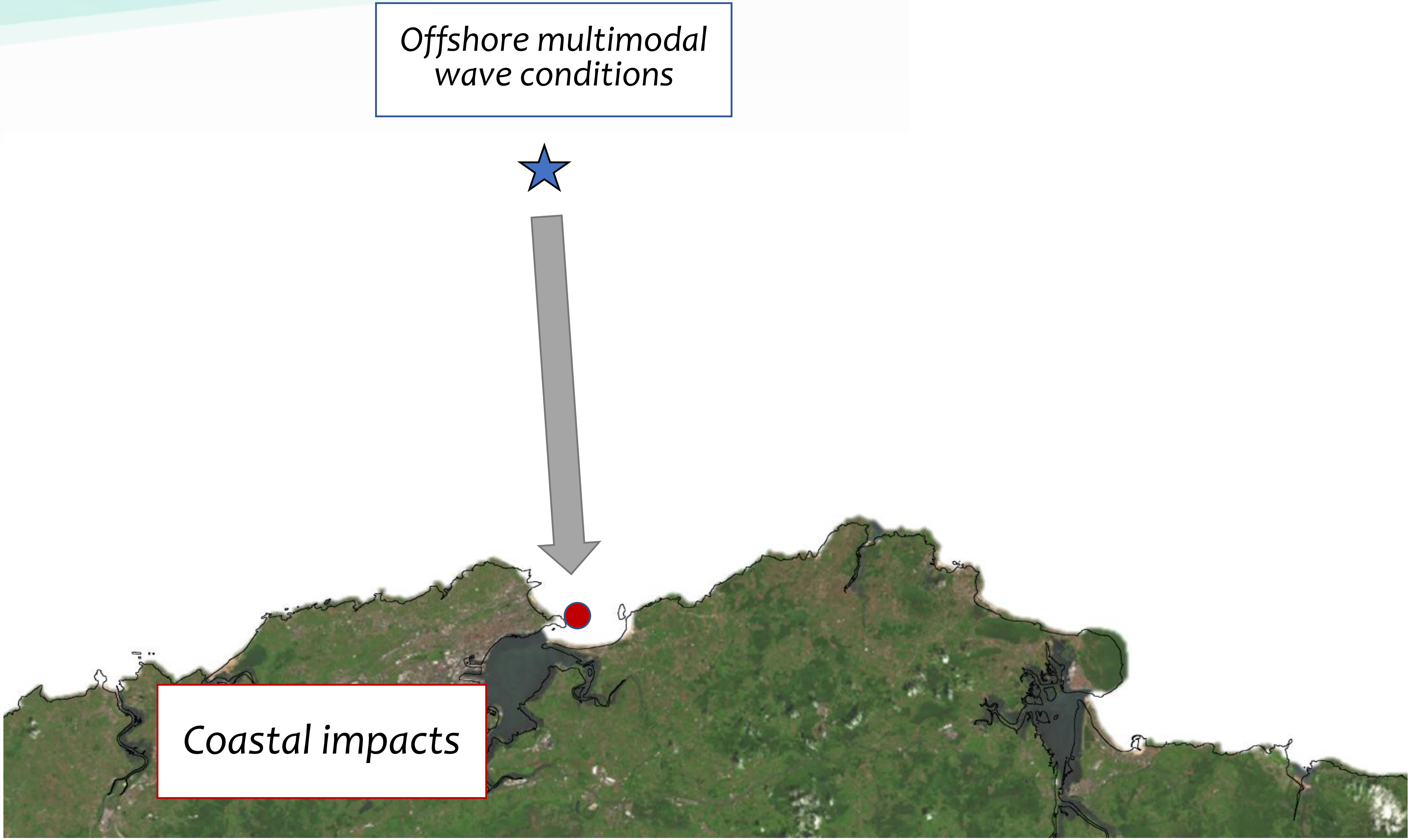
March 2014. Somo Beach (Cantabria)

August 2025. Caños de Meca Beach (Cadiz)



Coastal impacts

Motivation

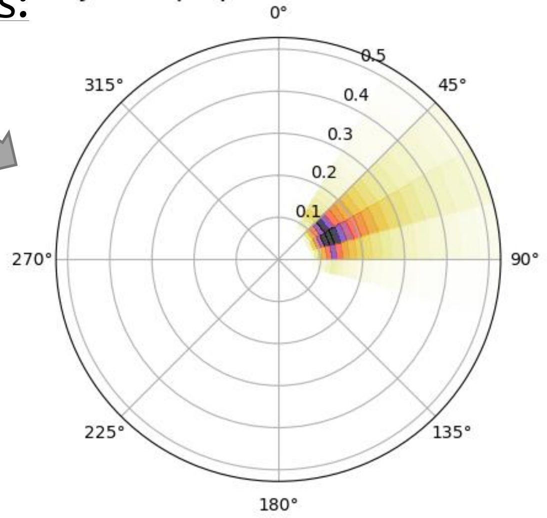


Motivation

Offshore multimodal wave conditions

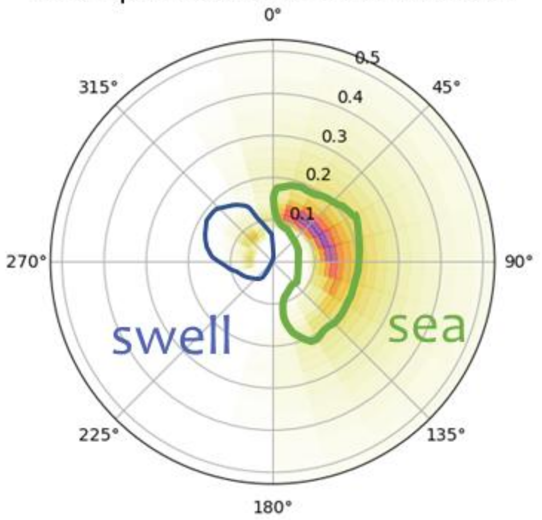
Bulk parameters:

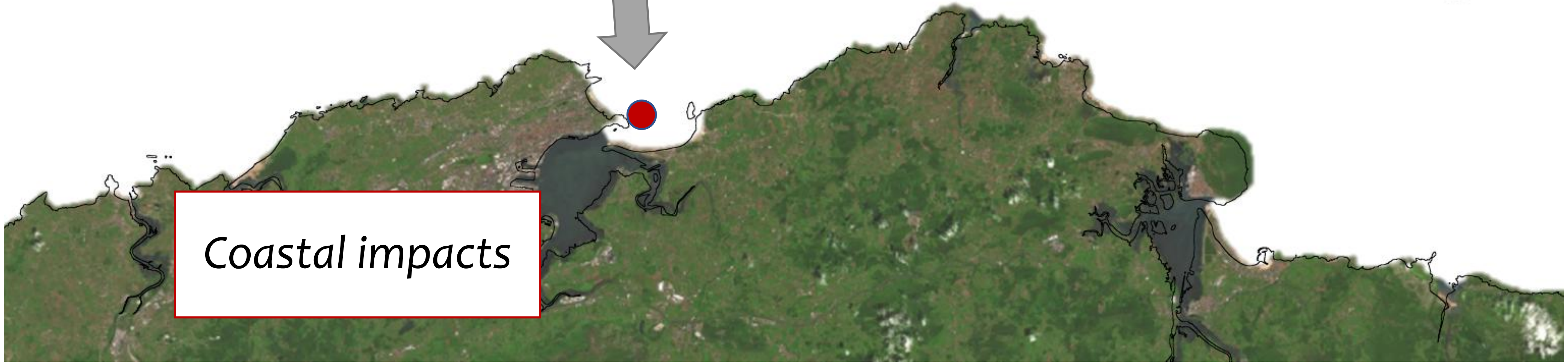
Hs = 2.5 m
Tp = 13 s
Dir = 75°



Wave spectrum:

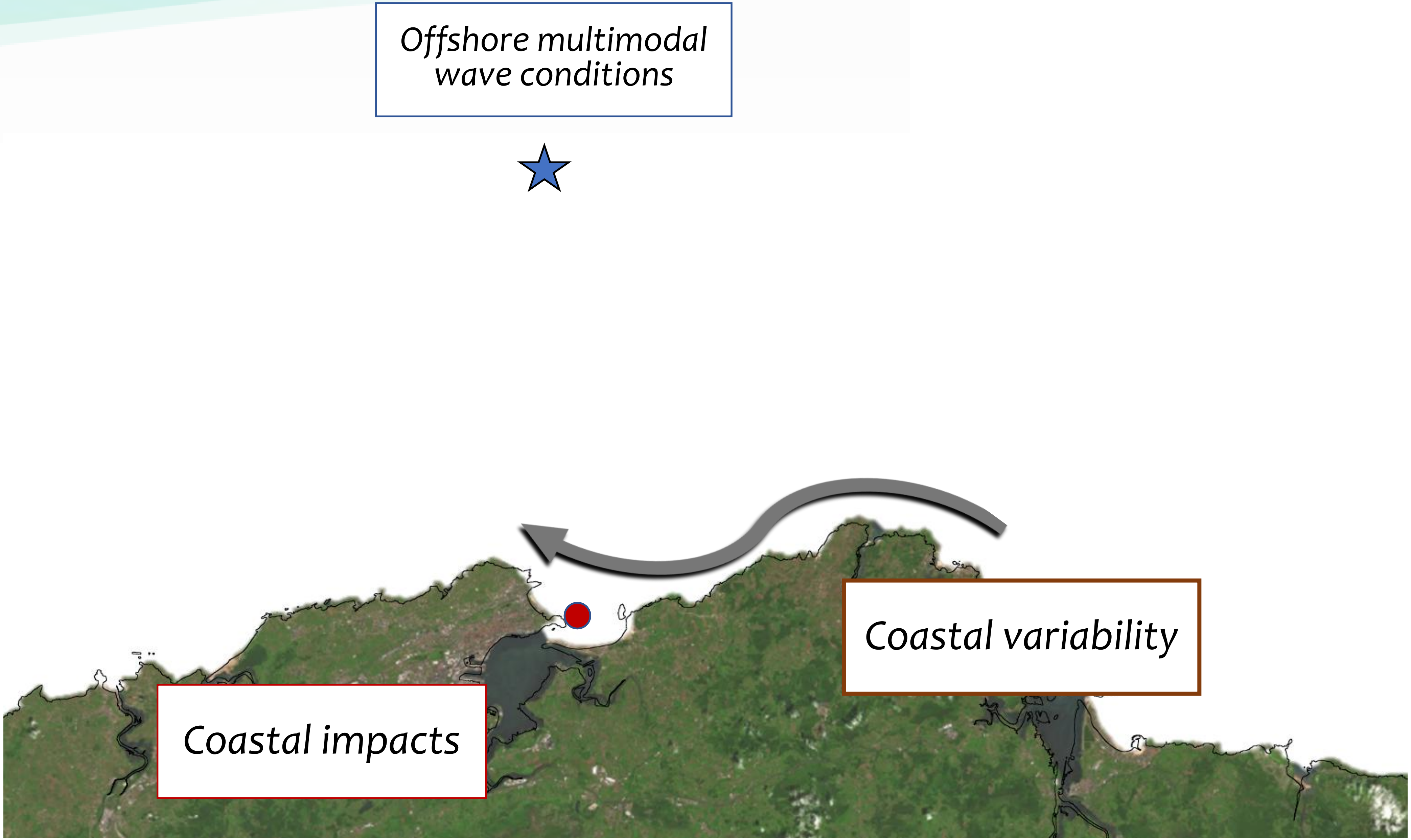
$S\ (f, \theta)$





Coastal impacts

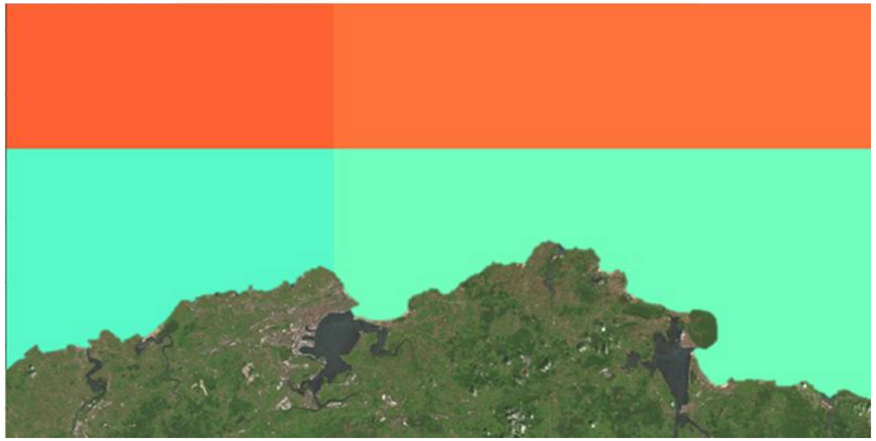
Motivation


Offshore multimodal wave conditions
Coastal variability
Coastal impacts

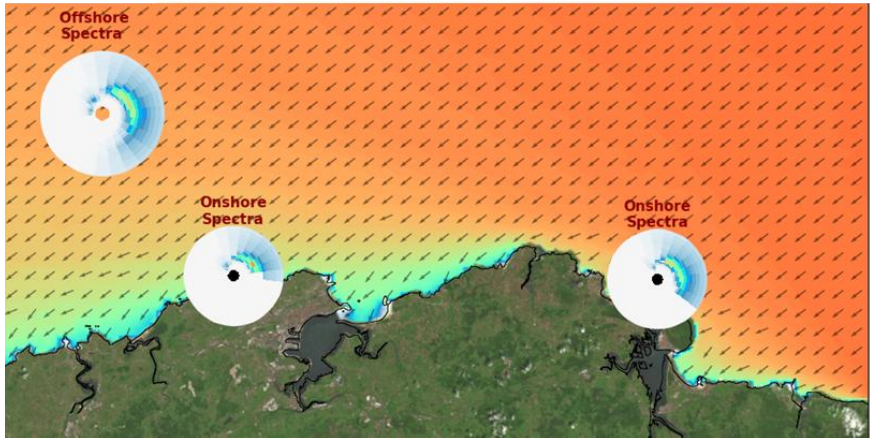
Motivation

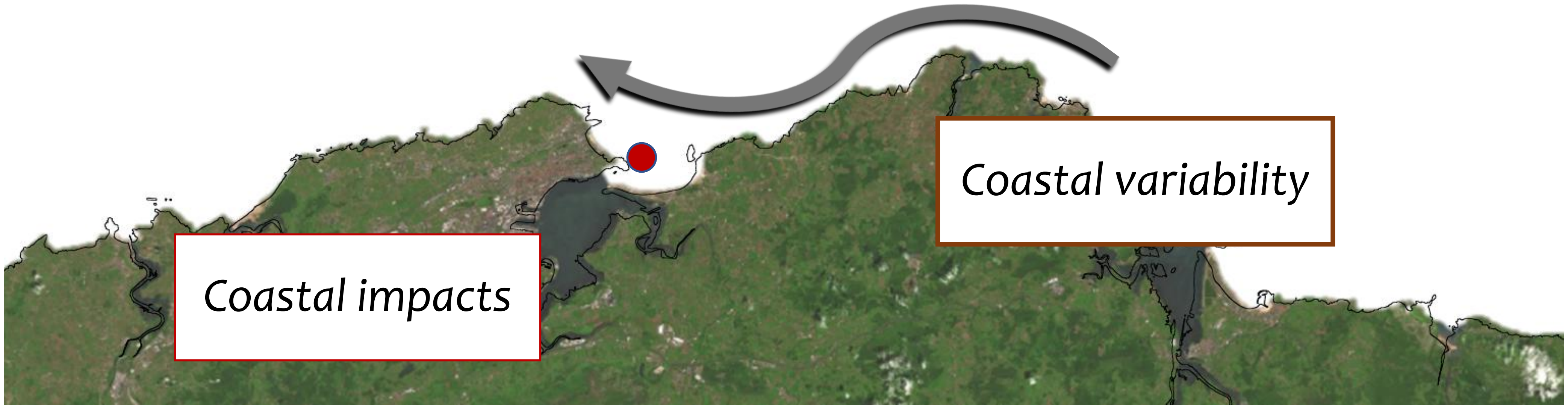
Offshore multimodal wave conditions

LOW RESOLUTION (50 km)



HIGH RESOLUTION (50 m)





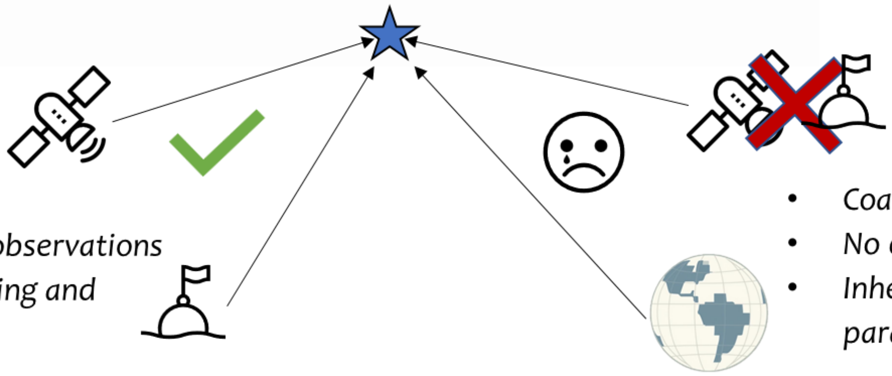
Coastal variability

Coastal impacts

Motivation

UC | Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

Offshore multimodal wave conditions



Hindcast

- *High-resolution output*
- *Direct validation against observations*
- *High-resolution wind forcing and calibrated model grids*

Projections

- *Coarse-resolution output*
- *No direct validation against observations*
- *Inherit GCM errors: spatial resolution, parameterizations, internal variability*

	Hindcast	Projections
Bulk parameters	0.25°	0.5°
Wave spectra	0.5°	10°
Forcing resolution	0.25	1 to 2°
Inherit errors		

From bulk to spectra

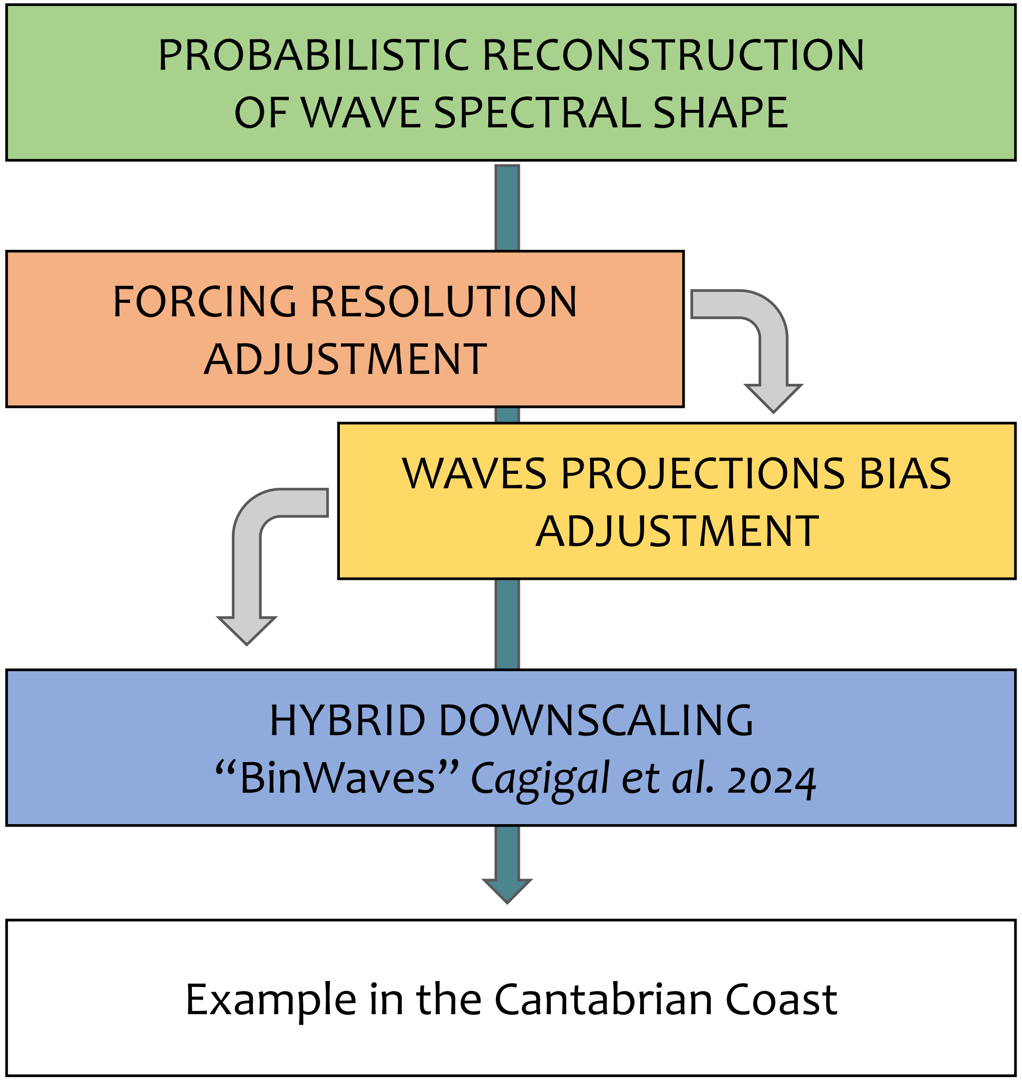
Bias correction

Forcing resolution correction

Objectives

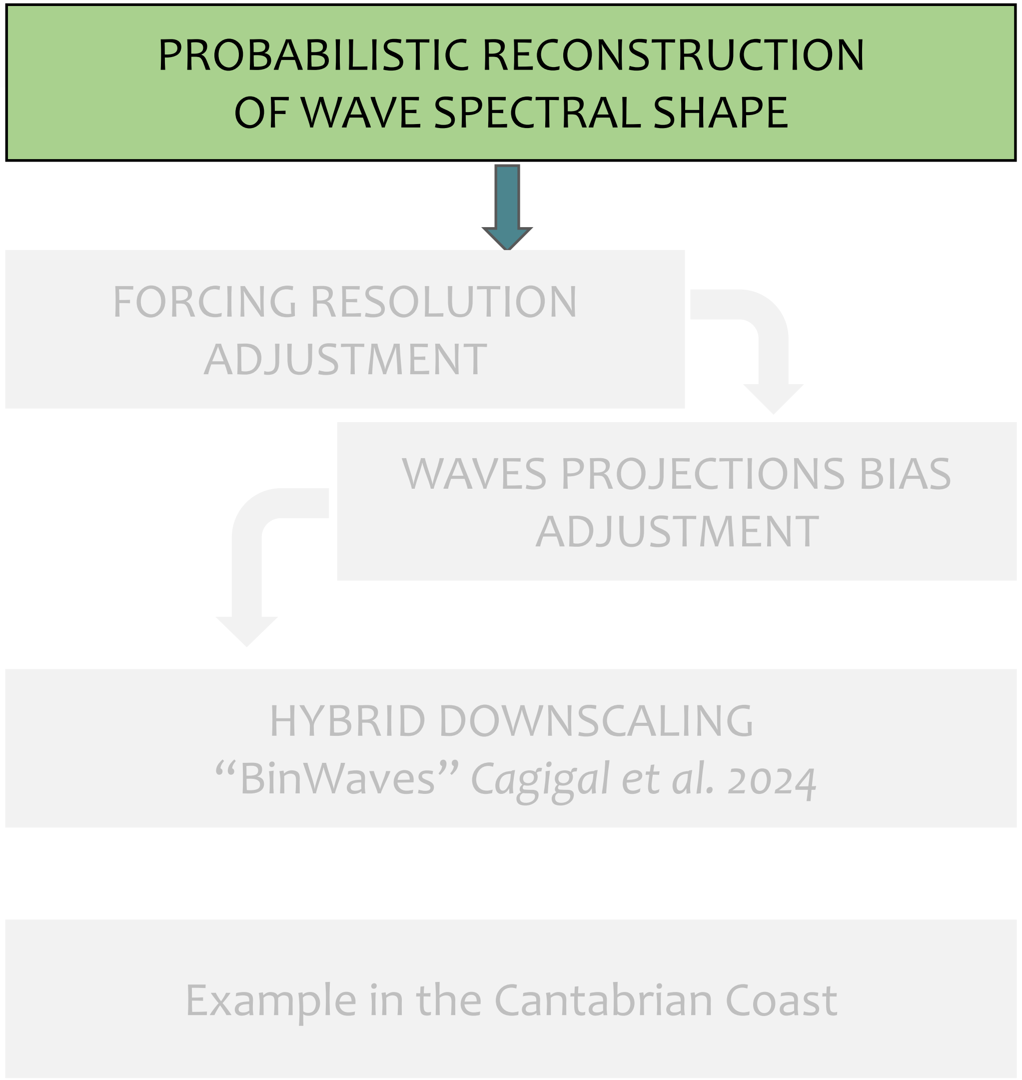
“Fast way to bring high-resolution climate projections to the coast”

1. Reconstruct the spectral shape from bulk parameters
2. Forcing resolution and Bias correction
3. Hybrid downscaling to coast
4. Example in the Cantabrian coast



Step by step

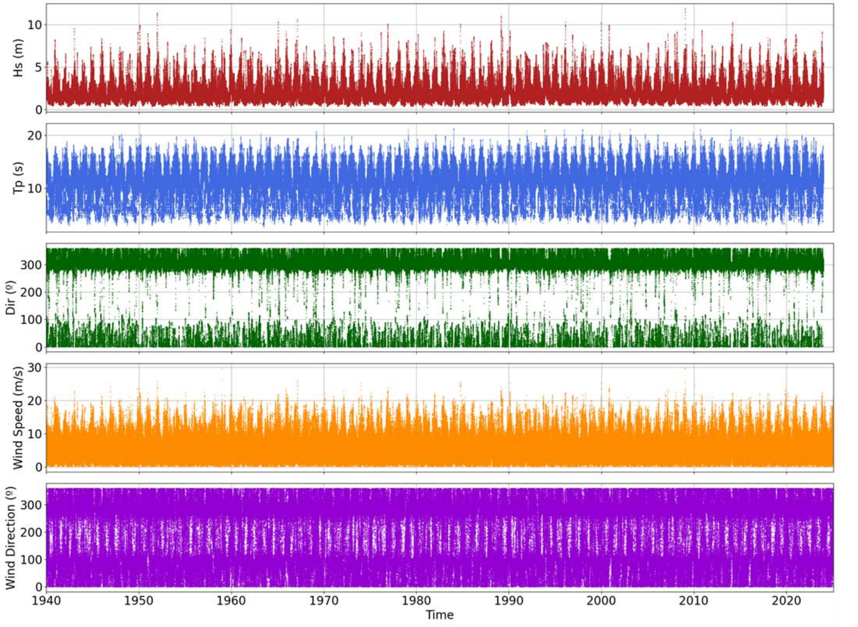
1. Reconstruct the spectral shape from bulk parameters



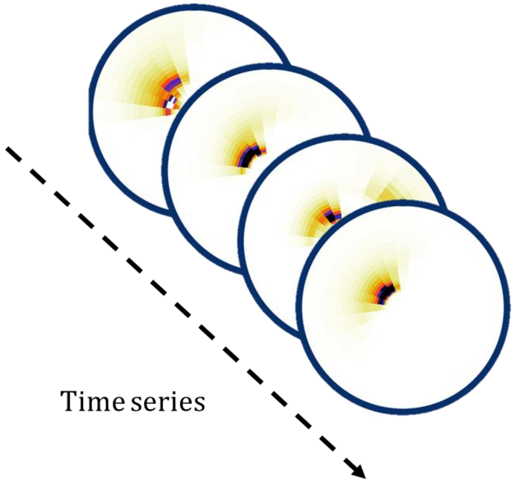
1. From Bulk Parameters to Spectra

UC | Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

Clustering **ERA5 reanalysis** (*Hersbach et al., 2020*):



Time series



PROBABILISTIC RECONSTRUCTION OF WAVE SPECTRAL SHAPE

Bulk parameters: $H_s, T_p, \theta, U_{10}, V_{10}$

Clustering with: ***MDA** algorithm*

Directional wave spectra: $S(f, \theta)$

PCA

Clustering with: ***Kmeans** algorithm*

Conditional probabilities:

$$P\left(H_s, T_p, \theta, U_{10}, V_{10} \mid S(f_i, \theta_j)\right)$$

At any time **x**...

Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ $\rightarrow$ $S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$

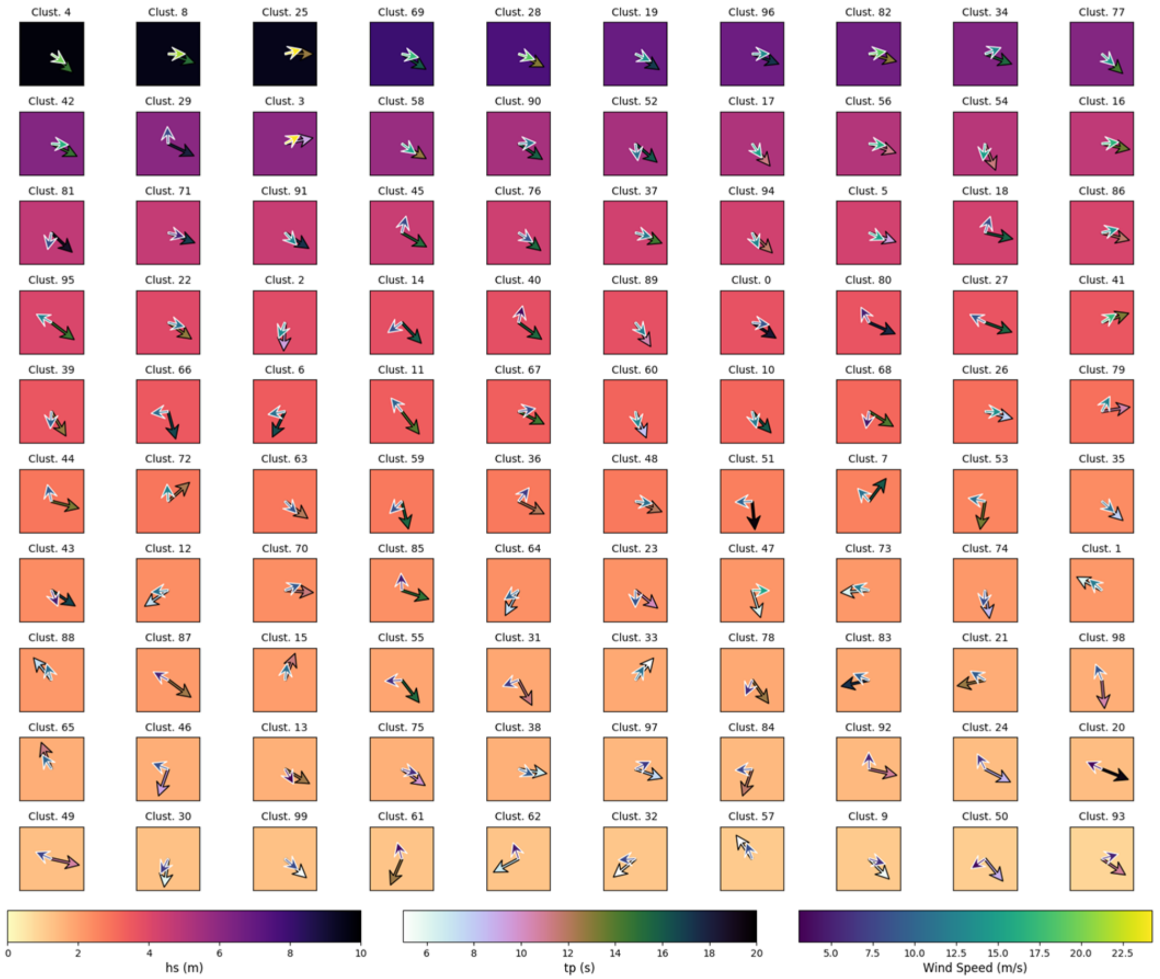
1. From Bulk Parameters to Spectra

UC | Universidad de Cantabria

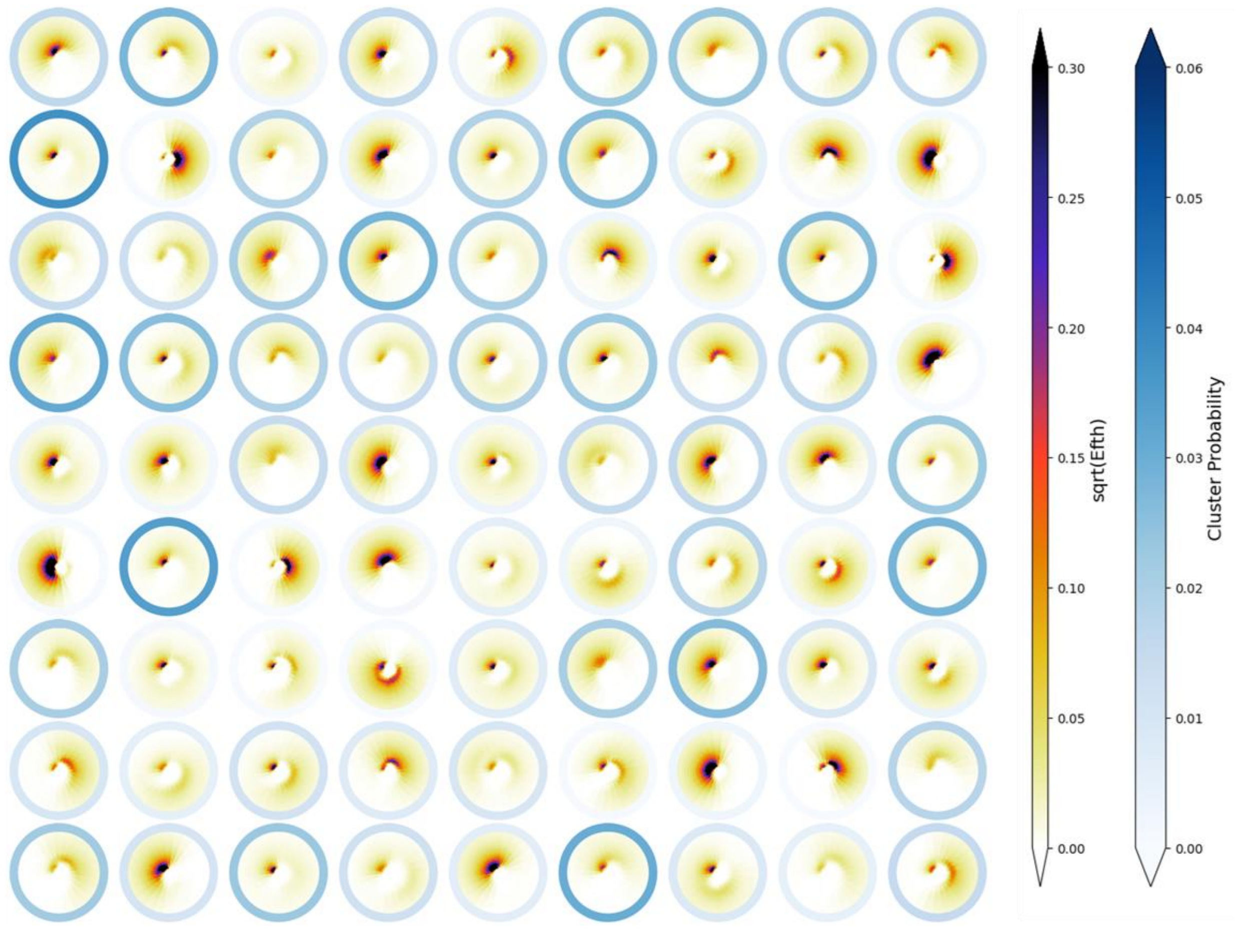
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

Clustering **Bulk parameters:**

100 MDA selected clusters

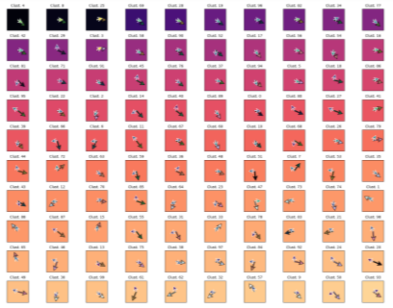


81 PCA + KMA clusters

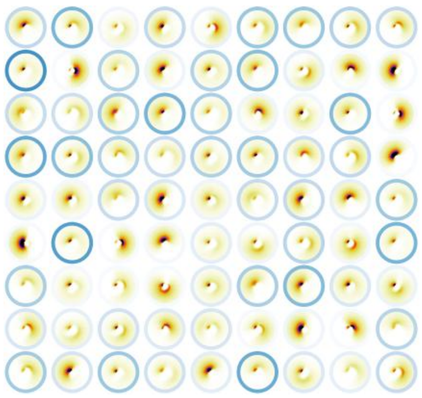


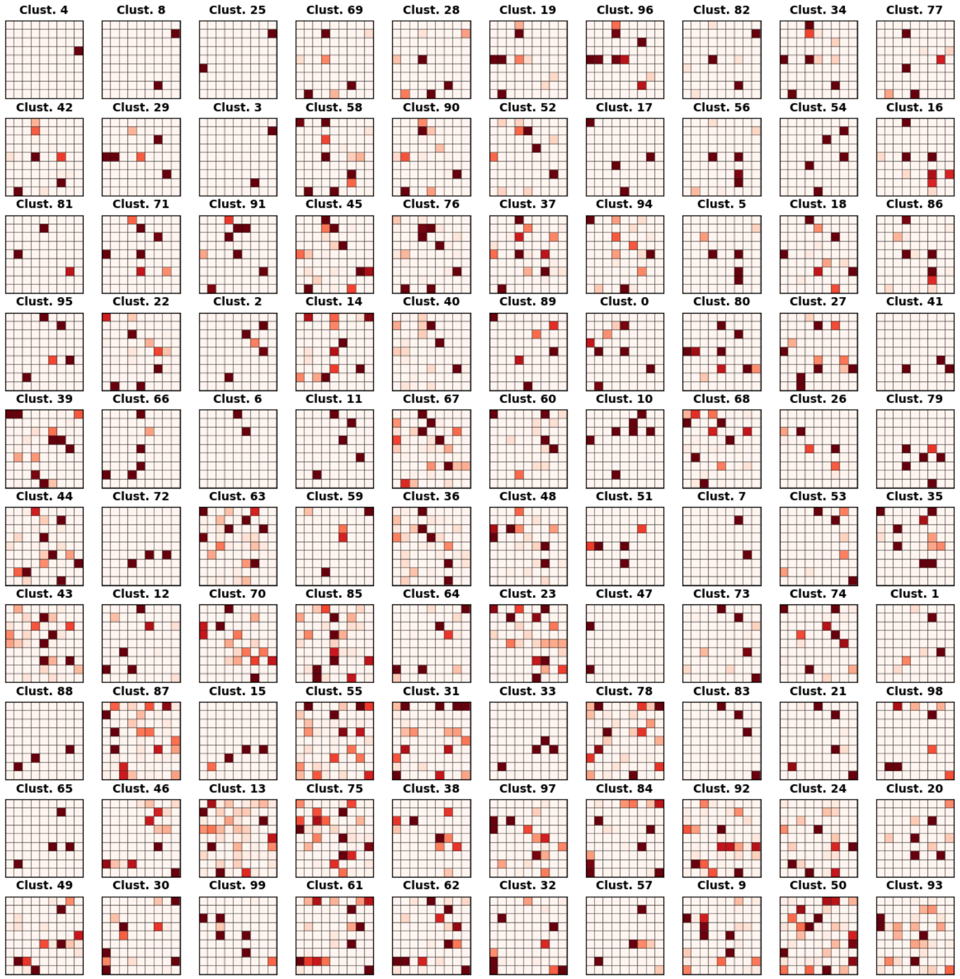
1. From Bulk Parameters to Spectra

Find **Conditional Probabilities** between bulk and spectra:



- 100 bulk clusters
- 81 spectra clusters





PROBABILISTIC RECONSTRUCTION OF WAVE SPECTRAL SHAPE

Bulk parameters: $H_s, T_p, \theta, U_{10}, V_{10}$

Directional wave spectra: $S(f, \theta)$

Clustering with: ***MDA** algorithm*

PCA

Clustering with: ***Kmeans** algorithm*

Conditional probabilities:

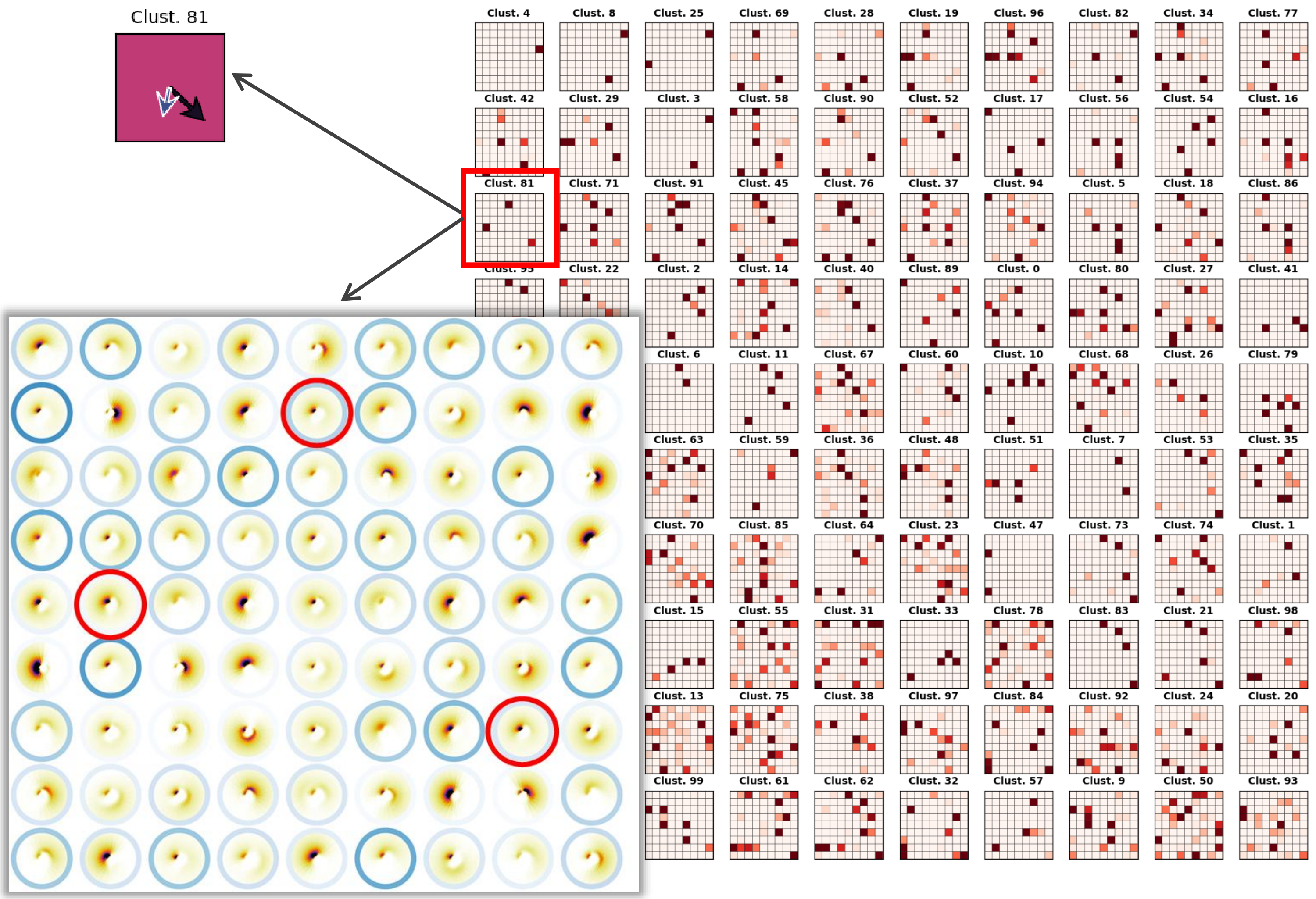
$$P\big(H_s, T_p, \theta, U_{10}, V_{10} \,\big|\, S(f_i, \theta_j)\big)$$

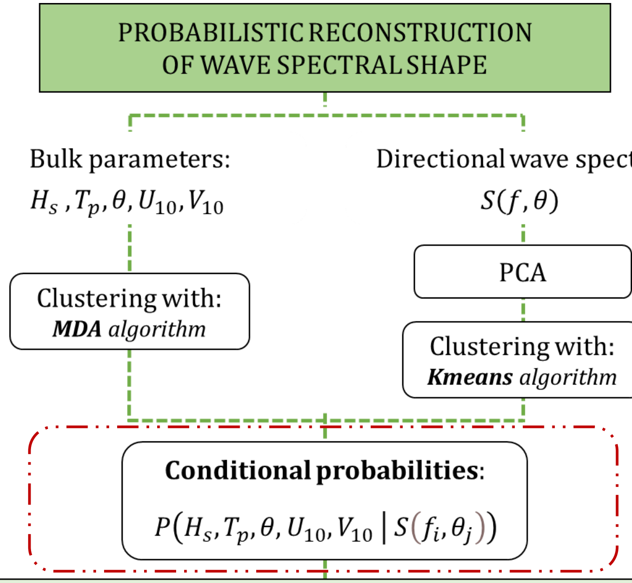
At any time **x**...

Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ $\rightarrow$ $$S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$$

1. From Bulk Parameters to Spectra

Find **Conditional Probabilities** between bulk and spectra:





At any time **x**...

Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ $\rightarrow$ $S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$

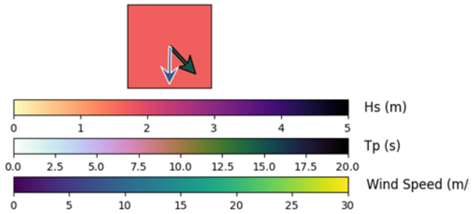
1. From Bulk Parameters to Spectra

At any time **x**...

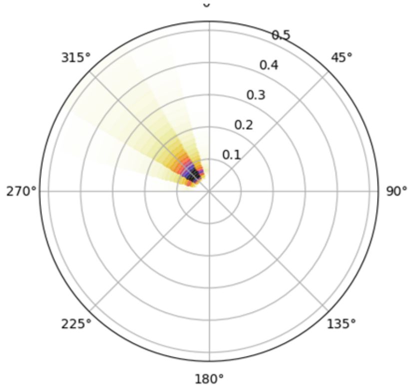
Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ → $S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$

Time case: 1995-01-09T08:00

Hindcast Bulk Parameter



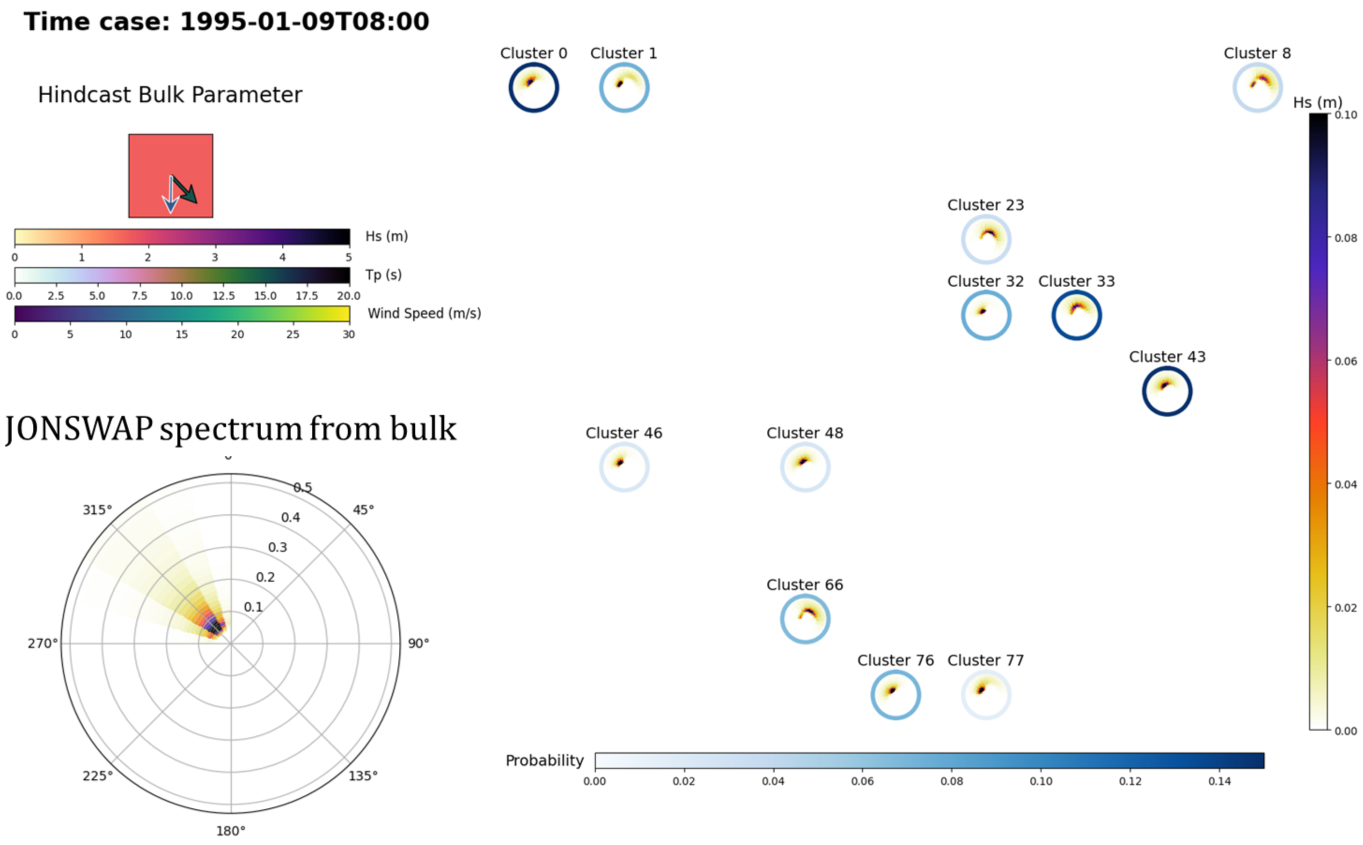
JONSWAP spectrum from bulk



1. From Bulk Parameters to Spectra

At any time **x**...

Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ $\rightarrow$ $S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$



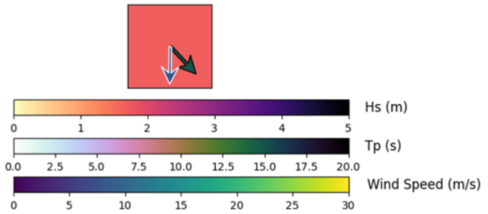
1. From Bulk Parameters to Spectra

At any time **x**...

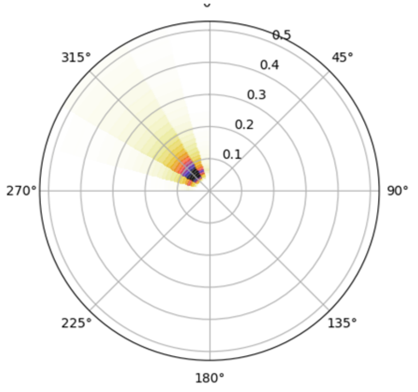
Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ $\rightarrow$ $S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$

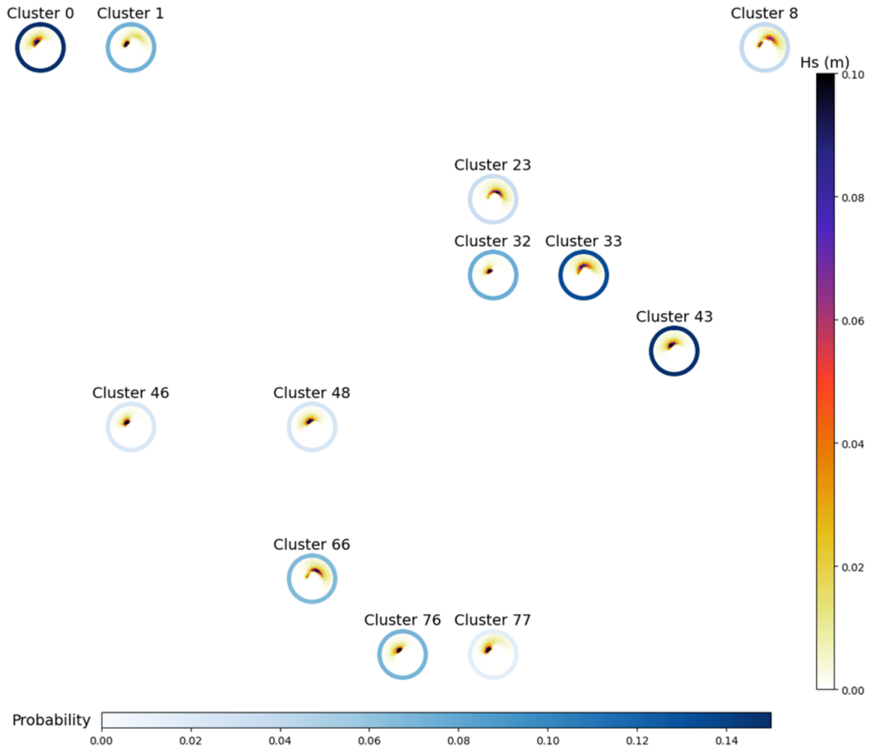
Time case: 1995-01-09T08:00

Hindcast Bulk Parameter



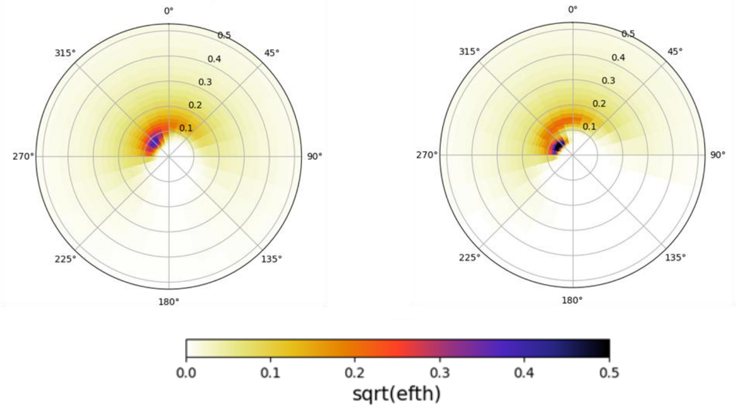
JONSWAP spectrum from bulk





Reconstructed spectrum

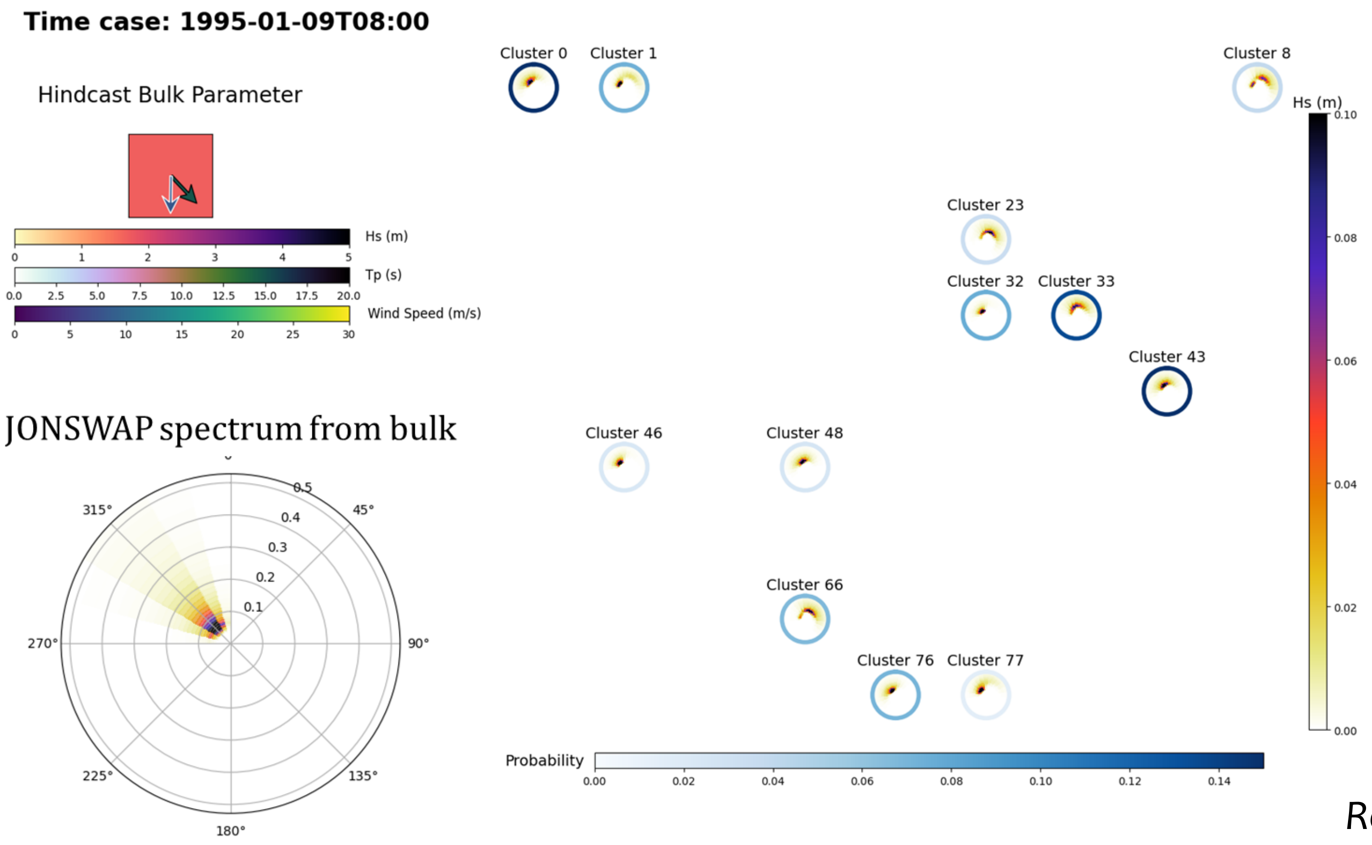
Real spectrum

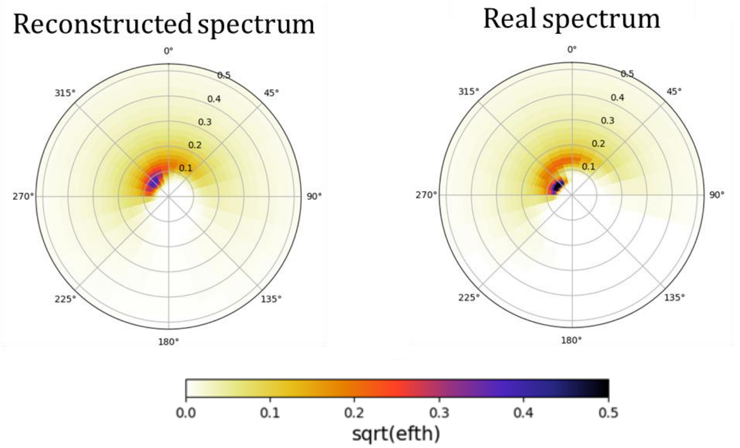


1. From Bulk Parameters to Spectra

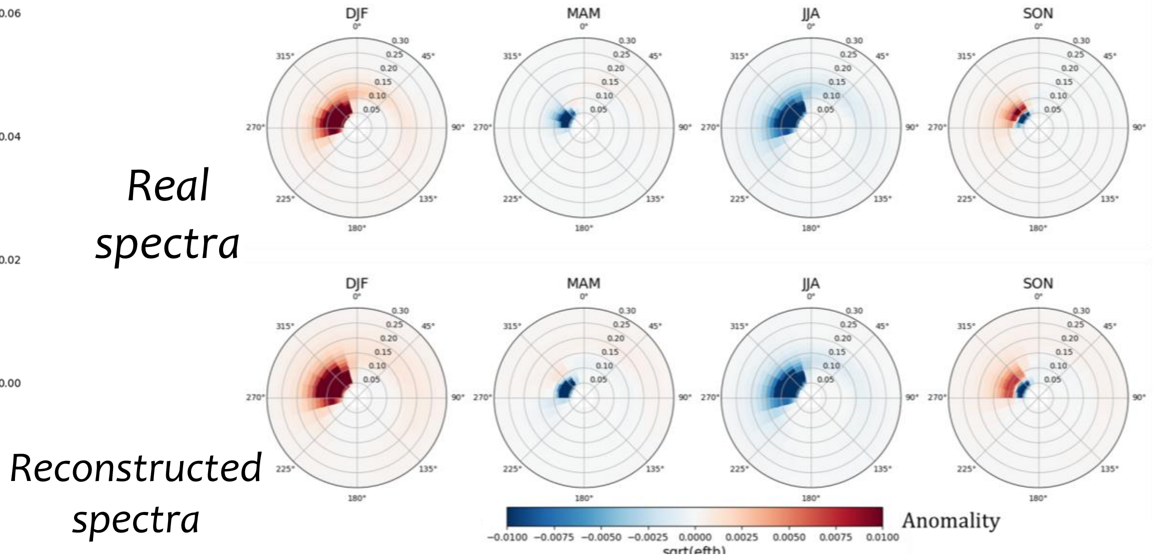
At any time **x**...

Starting from the bulk parameters $H_{sx}, T_{px}, \theta_x, U_{10x}, V_{10x}$ → $S_x(f,\theta) = \sum_{i=1}^{N} P_i * S_i(f,\theta) * \left(\frac{H_{sx}^2}{H_{si}^2}\right)$



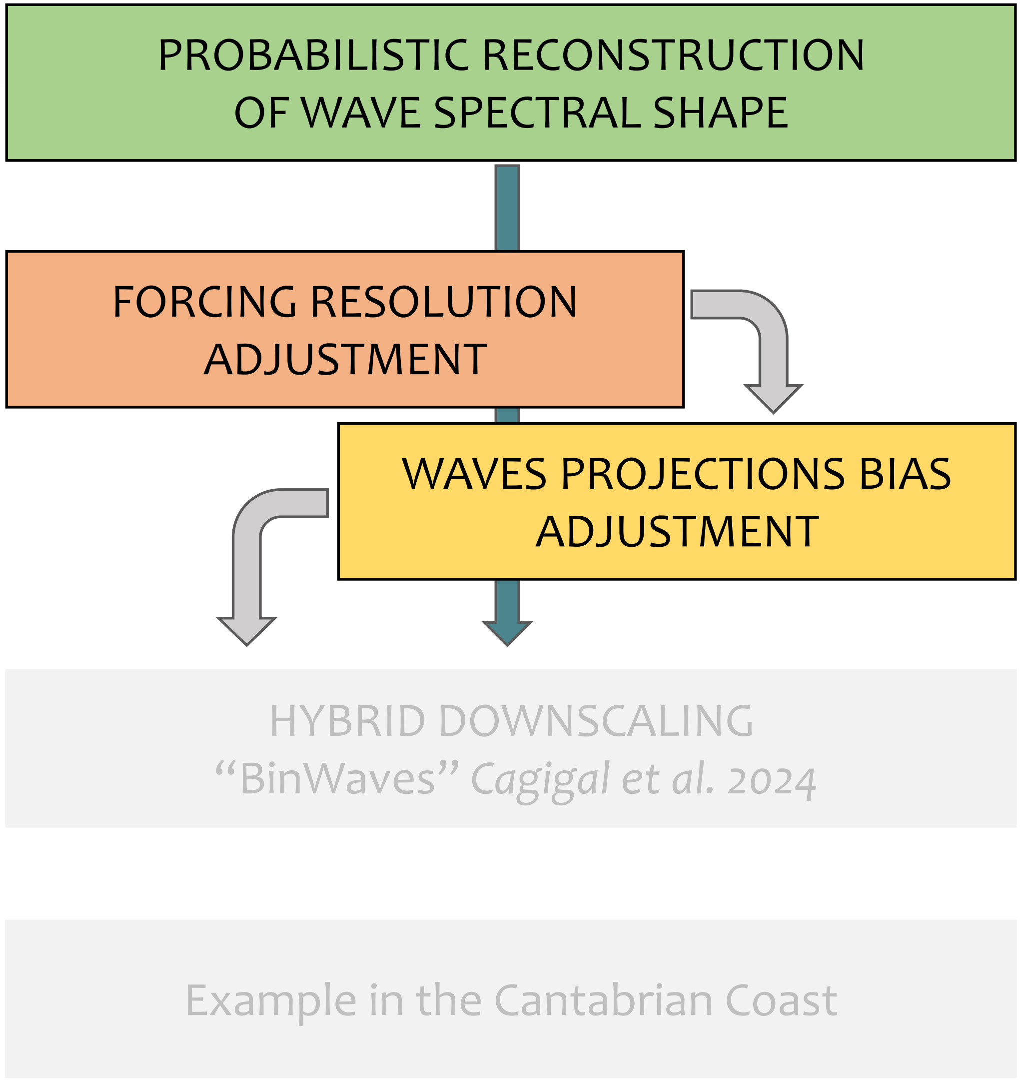


5 years seasonal validation



Step by step

1. ~~Reconstruct the spectral shape from bulk parameters~~
2. Forcing resolution and Bias correction



2. Forcing resolution and Bias correction

UC | Universidad de Cantabria

Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

BIAS origin:

- Wind forcing regridded to regular WW3 grid
- Simplified physics and parameterizations in GCMs)

BIAS effects:

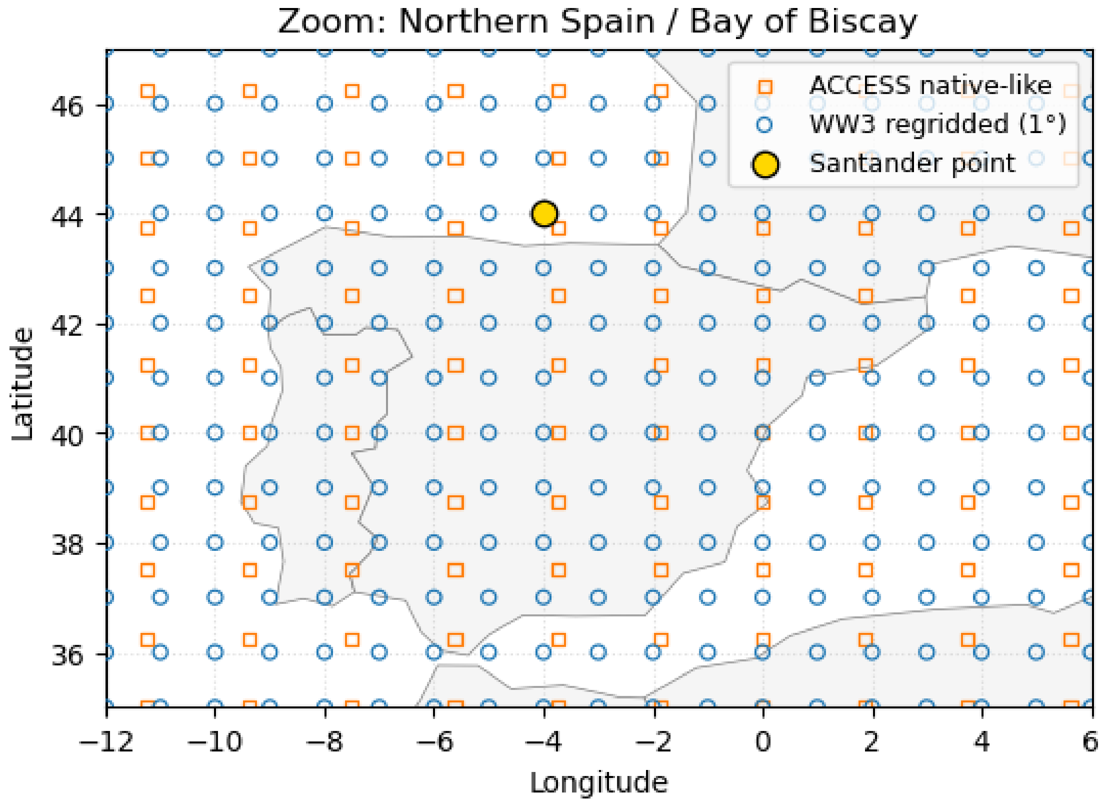
- Interpolation smooths wind fields
- Results in systematic bias in wave heights

140 Years of Global Ocean Wind-Wave Climate Derived from CMIP6 ACCESS-CM2 and EC-Earth3 GCMs: Global Trends, Regional Changes, and Future Projections

ALBERTO MEUCCI,[a] IAN R. YOUNG,[a] MARK HEMER,[b] CLAIRE TRENHAM,[c] AND IAN G. WATTERSON[d]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria, Australia*
[b] *CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia*
[c] *CSIRO Oceans and Atmosphere, Canberra, Australian Capital Territory, Australia*
[d] *CSIRO Climate Science Centre, Aspendale, Victoria, Australia*

(Manuscript received 2 December 2021, in final form 8 November 2022)



2. Forcing resolution and Bias correction

UC | Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

BIAS CORRECTION DUE TO WIND FORCING RESOLUTION

Point-by-point comparison of directional wave spectra from WW3 simulations at 2° and 0.5° wind resolution.

Derive **directional correction coefficients** (**a** and **b**) for **SEA** and **SWELL** partitions using the power-law relation (**Hs* = a·Hs^b**)

Apply correction at the target location (**Santander coastal point**)

<u>WORKING ON IT</u>

DIRECTIONAL BIAS CORRECTION (QDM)

Calibrate: Compare ERA5 hindcast vs. GCM historical by directional sector

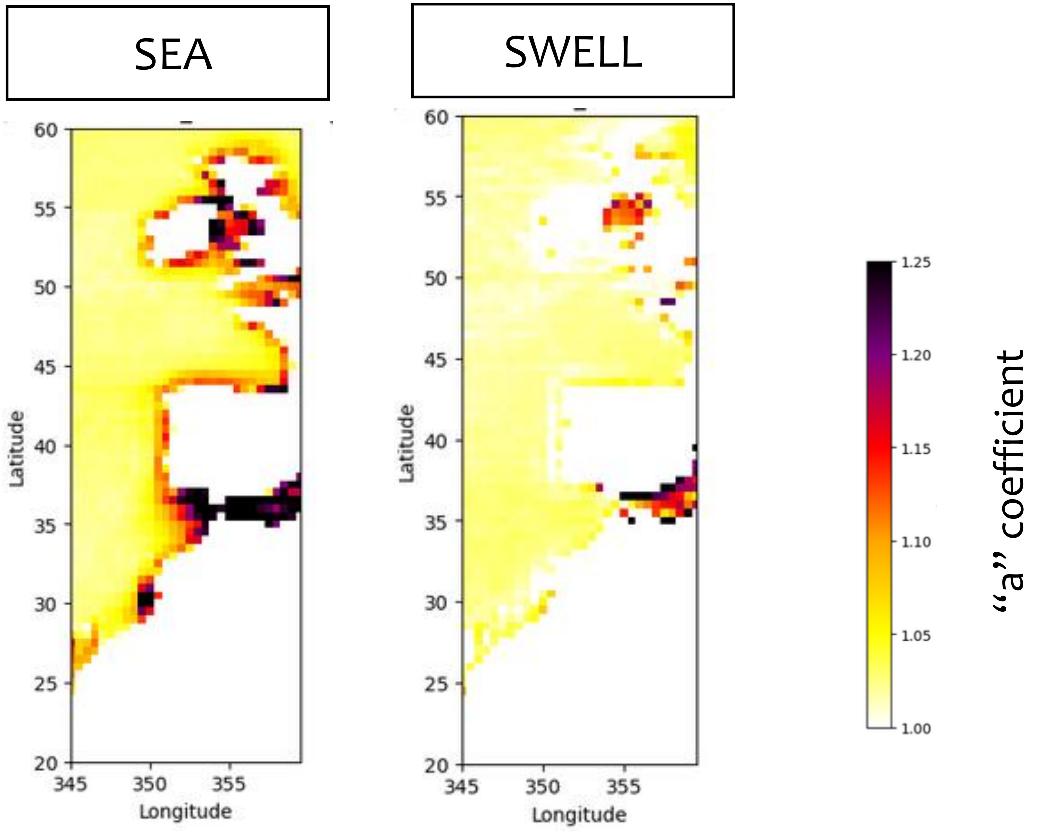
Quantile Delta Mapping (QDM): Derive quantile correction factors δ(q) per directional sector

Apply δ(q) to SSP126 and SSP585 projections by sector

2. Forcing resolution and Bias correction

Comparison: **WW3 hindcast forced with winds at 2° vs. 0.5°** (year 2017): $H_s' = aH_s^b$

- Stronger bias in sea partition than in swell in coastal zones
- Regridded wind forcing mainly impacts locally generated waves (sea)



BIAS CORRECTION DUE TO WIND FORCING RESOLUTION

Point-by-point comparison of directional wave spectra from WW3 simulations at 2° and 0.5° wind resolution.

Derive **directional correction coefficients** (**a** and **b**) for **SEA** and **SWELL** partitions using the power-law relation (**Hs* = a·Hs^b**)

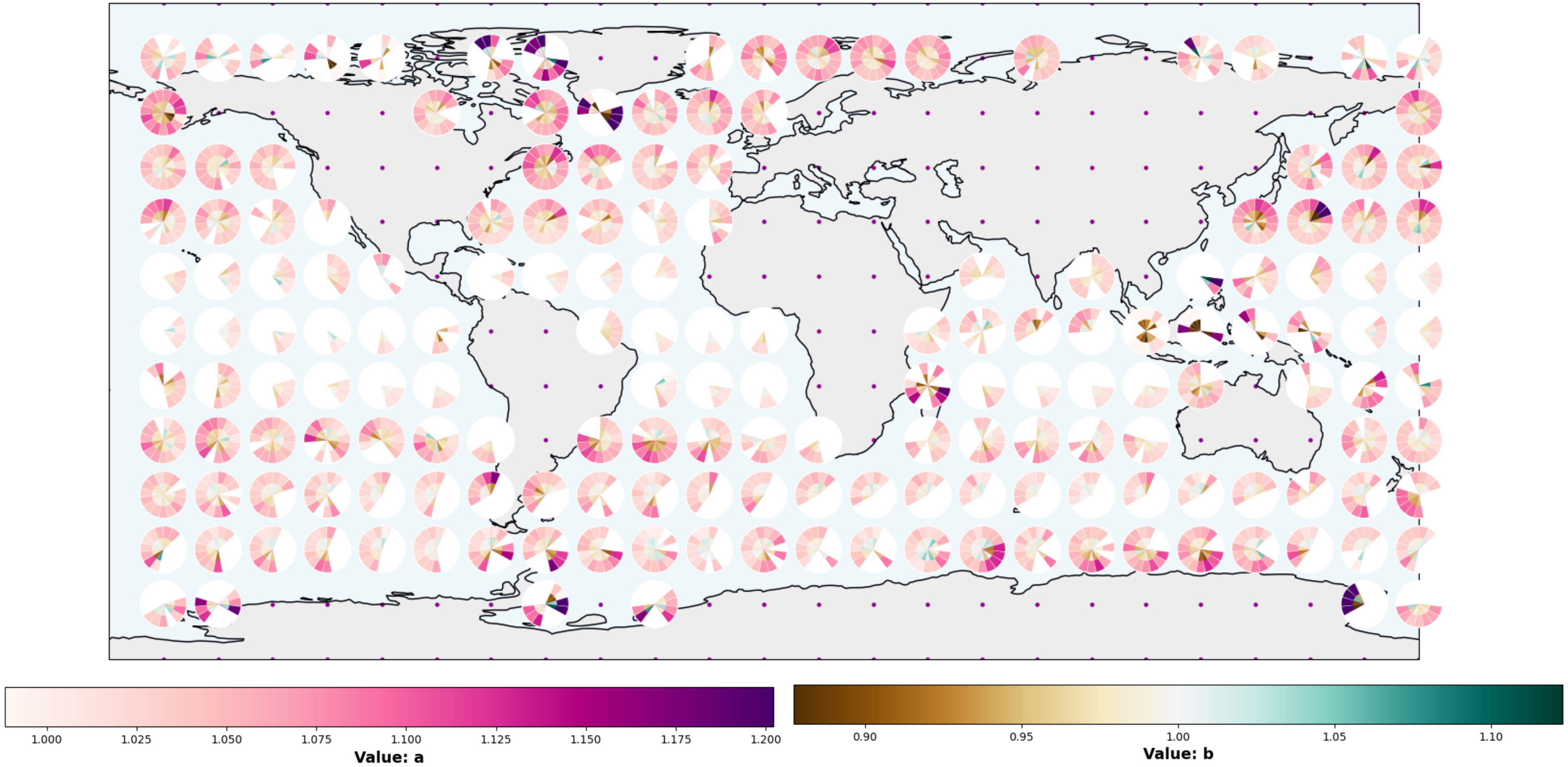
Apply correction at the target location (**Santander coastal point**)

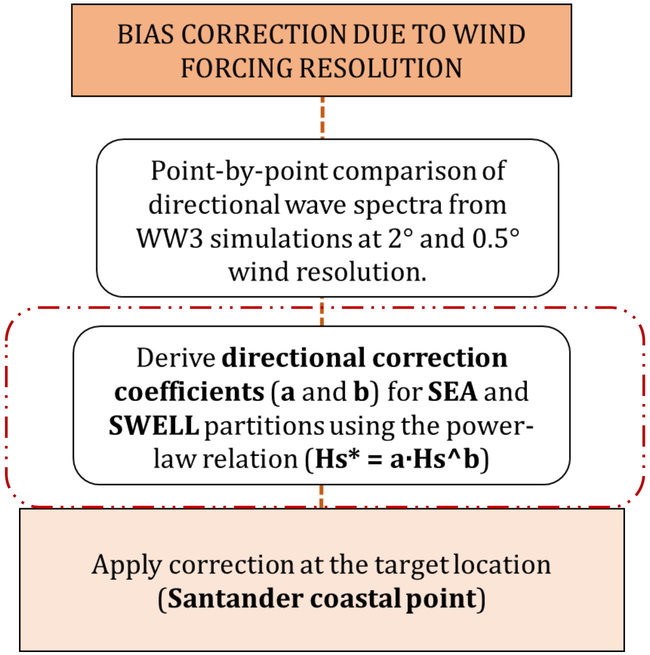
2. Forcing resolution and Bias correction

UC | Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

Comparison: **WW3 hindcast forced with winds at 2° vs. 0.5°** (year 2017): $H_s' = aH_s^b$

- Apply correction separately to SEA and SWELL Hs
- Correction performed for each directional sector (16 sectors)





2. Forcing resolution and Bias correction

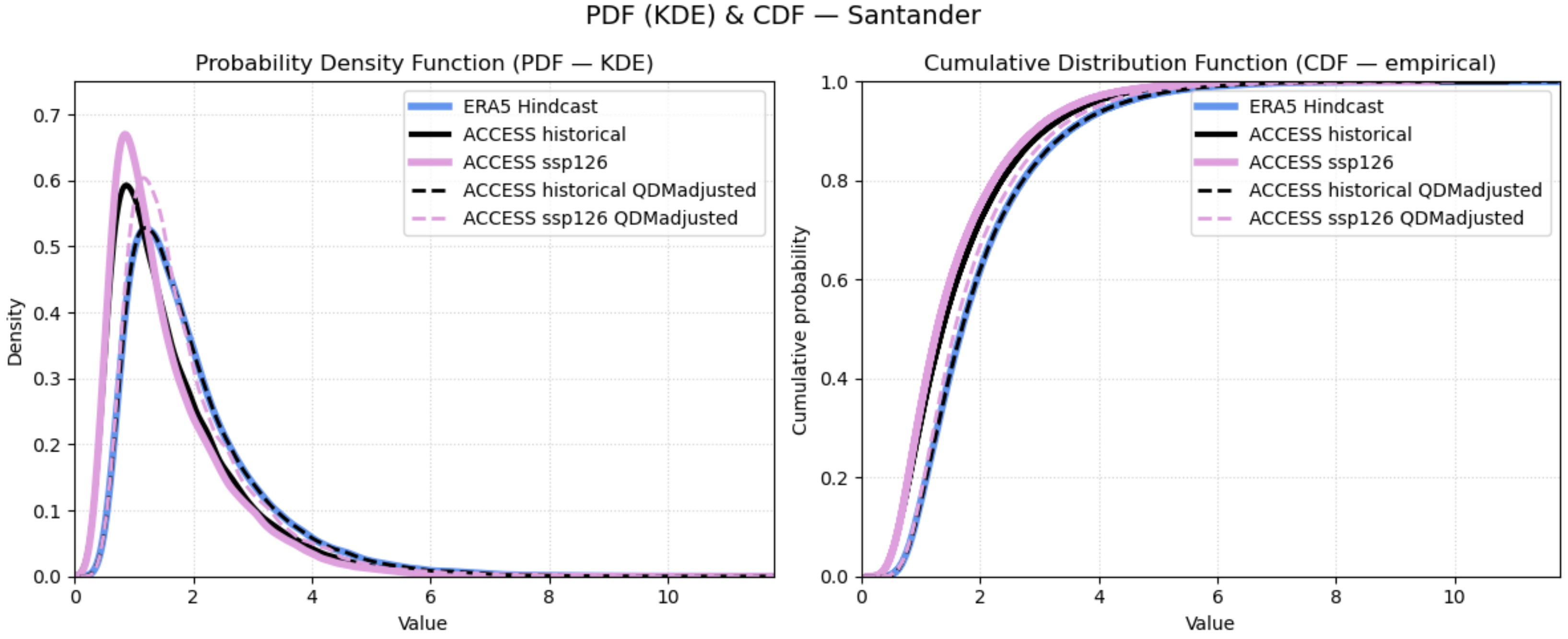
As in Lemos et al 2020:

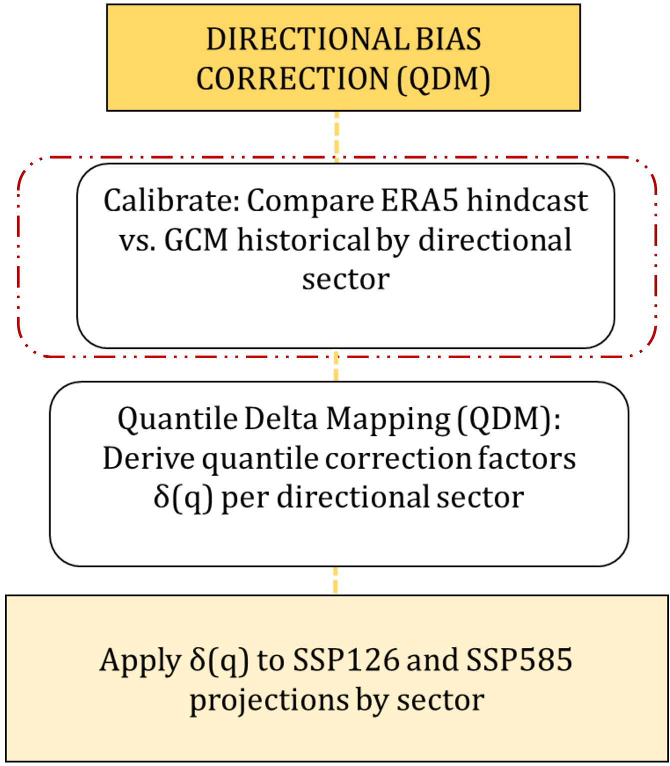
On the need of bias correction methods for wave climate projections

Gil Lemos[a,*], Melisa Menendez[b], Alvaro Semedo[c,a], Paula Camus[b], Mark Hemer[d], Mikhail Dobrynin[e], Pedro M.A. Miranda[a]

[a] Instituto Dom Luiz, Faculty of Sciences of the University of Lisbon, Lisbon, Portugal
[b] Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, Santander, Spain
[c] IHE Delft, Department of Water Science and Engineering, Westvest 7, 2611 Delft, the Netherlands
[d] CSIRO Oceans and Atmosphere, Hobart, TAS, Australia
[e] Institute of Oceanography, Center for Earth System Research and Sustainability (CEN), Hamburg, Germany

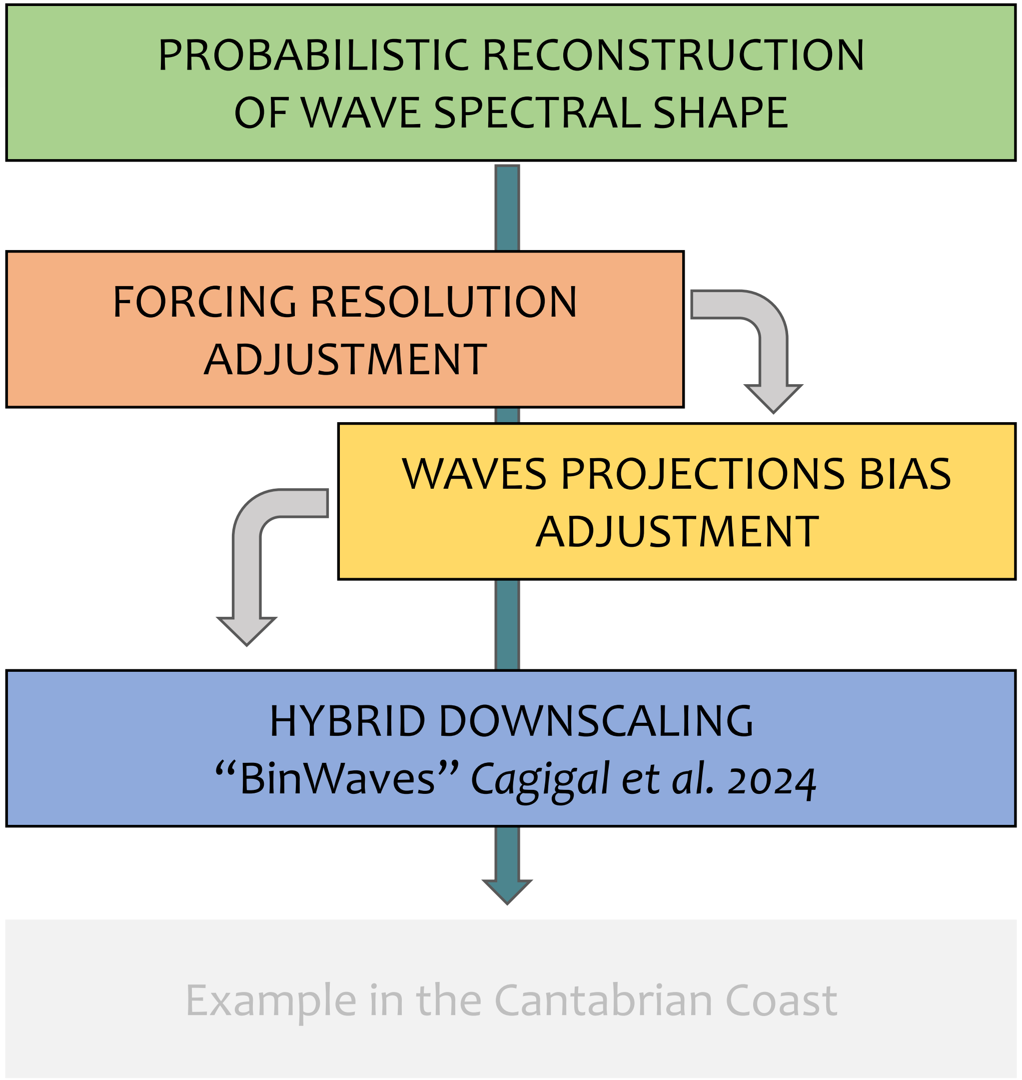
- QDM has been tried
- DAGQM is the goal, in order to keep quantiles and directional relation





Step by step

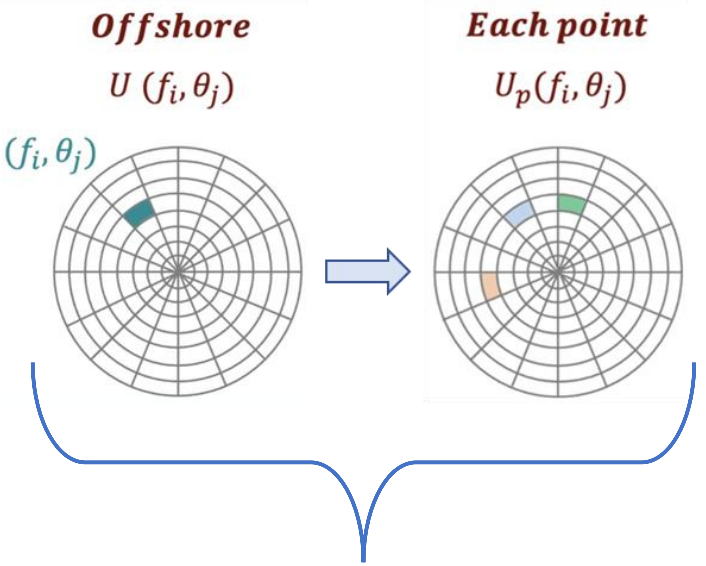
1. ~~Reconstruct the spectral shape from bulk parameters~~
2. ~~Forcing resolution and Bias correction~~
3. Hybrid downscaling to coast



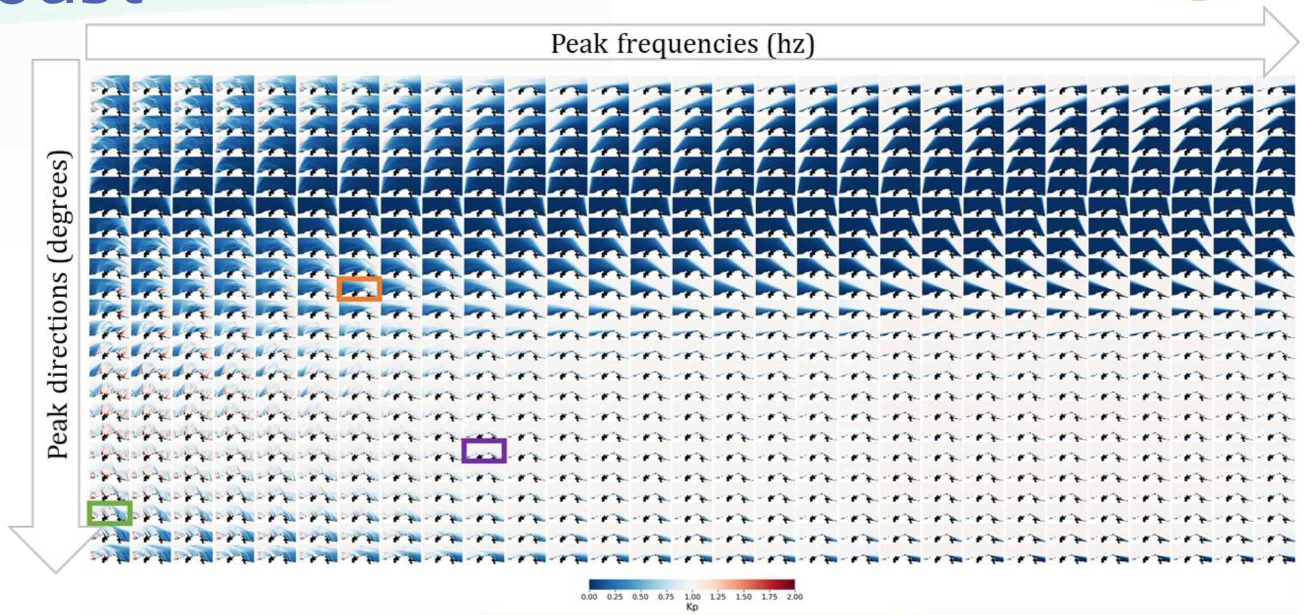
3. Hybrid downscaling to coast

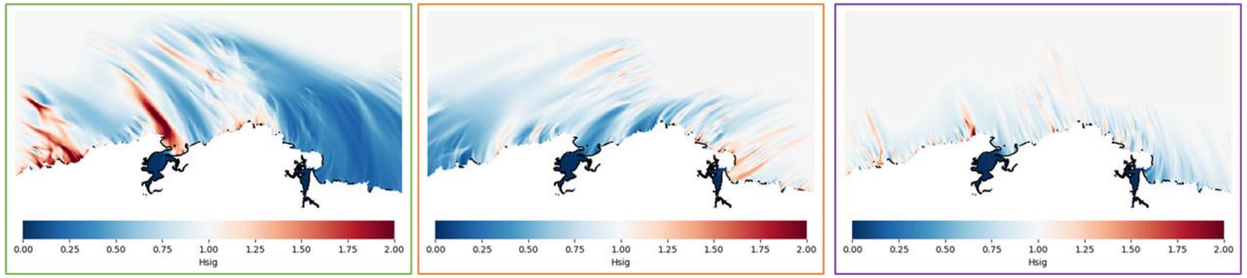
UC | Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

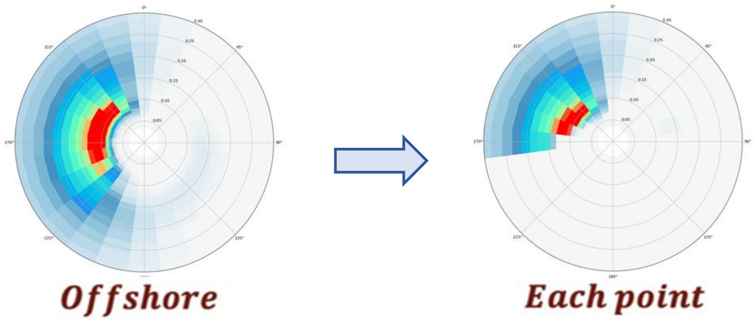
BinWaves (*Cagigal et al. 2024)*



$$K_p(f_i,\theta_j) = \frac{U_p(f_i,\theta_j)}{\iint U(f_i,\theta_j) d_f d_\theta}$$





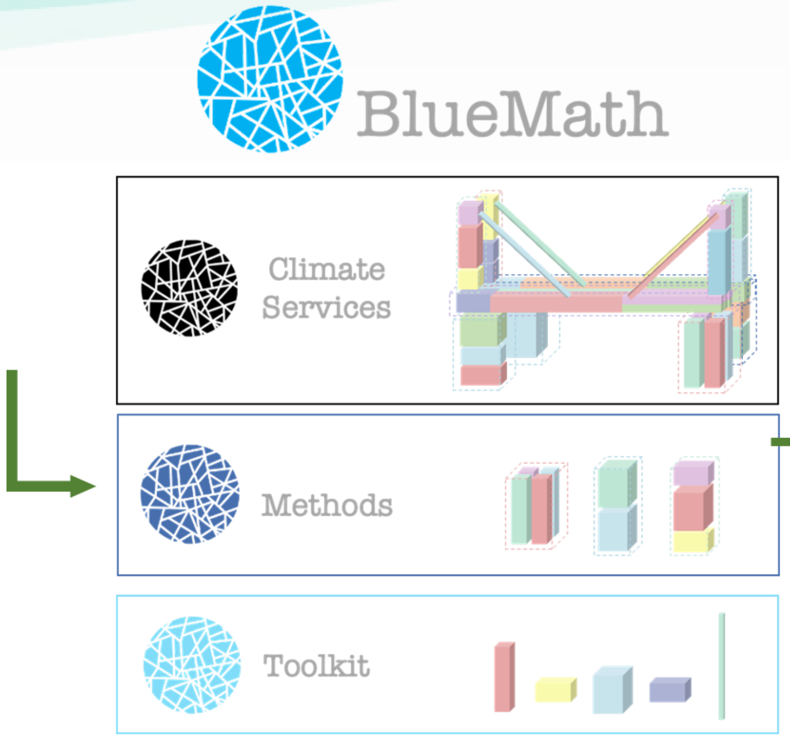


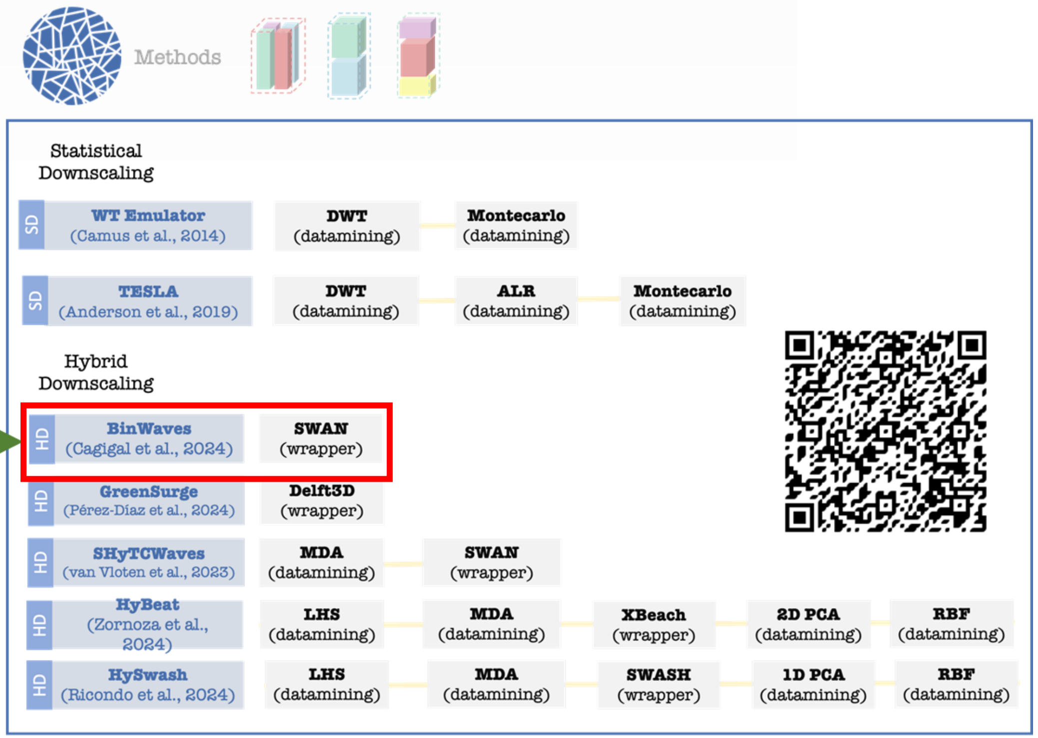
Spectral reconstruction at any point of the domain:

$$S_p(f_i,\theta_j) = \sum_i \sum_j S(f_i,\theta_j) * K_p^2(f_i,\theta_j)$$

3. Hybrid downscaling to coast

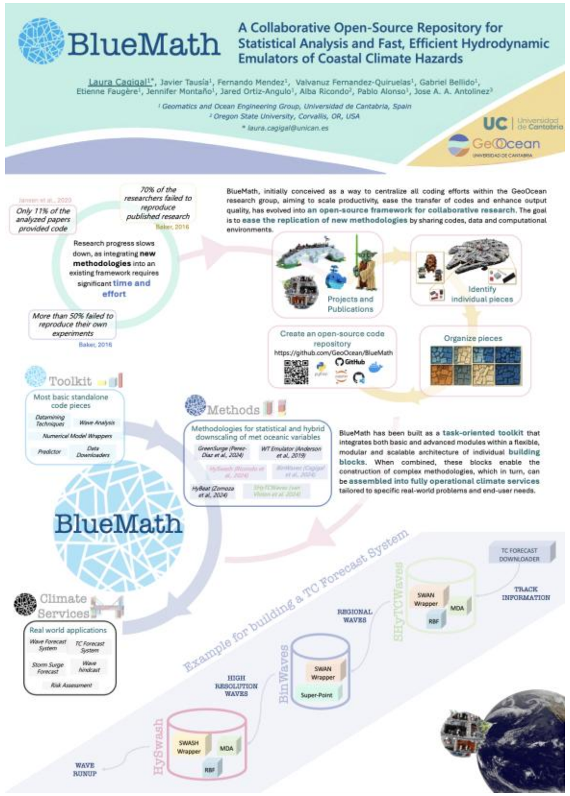
UC | Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA





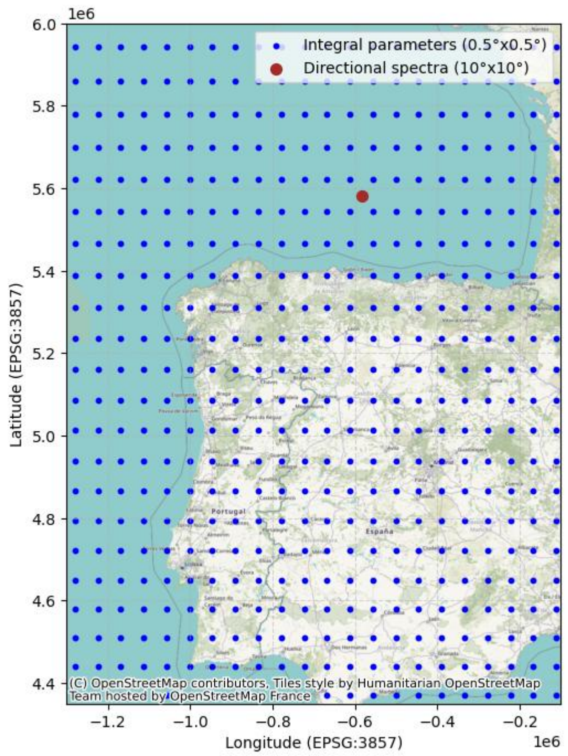
ROOM 2 Thursday between 15:05 and 15:10 : BlueMath, A Collaborative Open-Source Repository for Statistical Analysis and Fast, Efficient Hydrodynamic Emulators of Coastal Climate Hazards

POSTER PRESENTER: Laura Cagigal



Step by step

1. ~~Reconstruct the spectral shape from bulk parameters~~
2. ~~Bias correction~~
3. ~~Hybrid downscaling to coast~~
4. Example in the Cantabrian coast



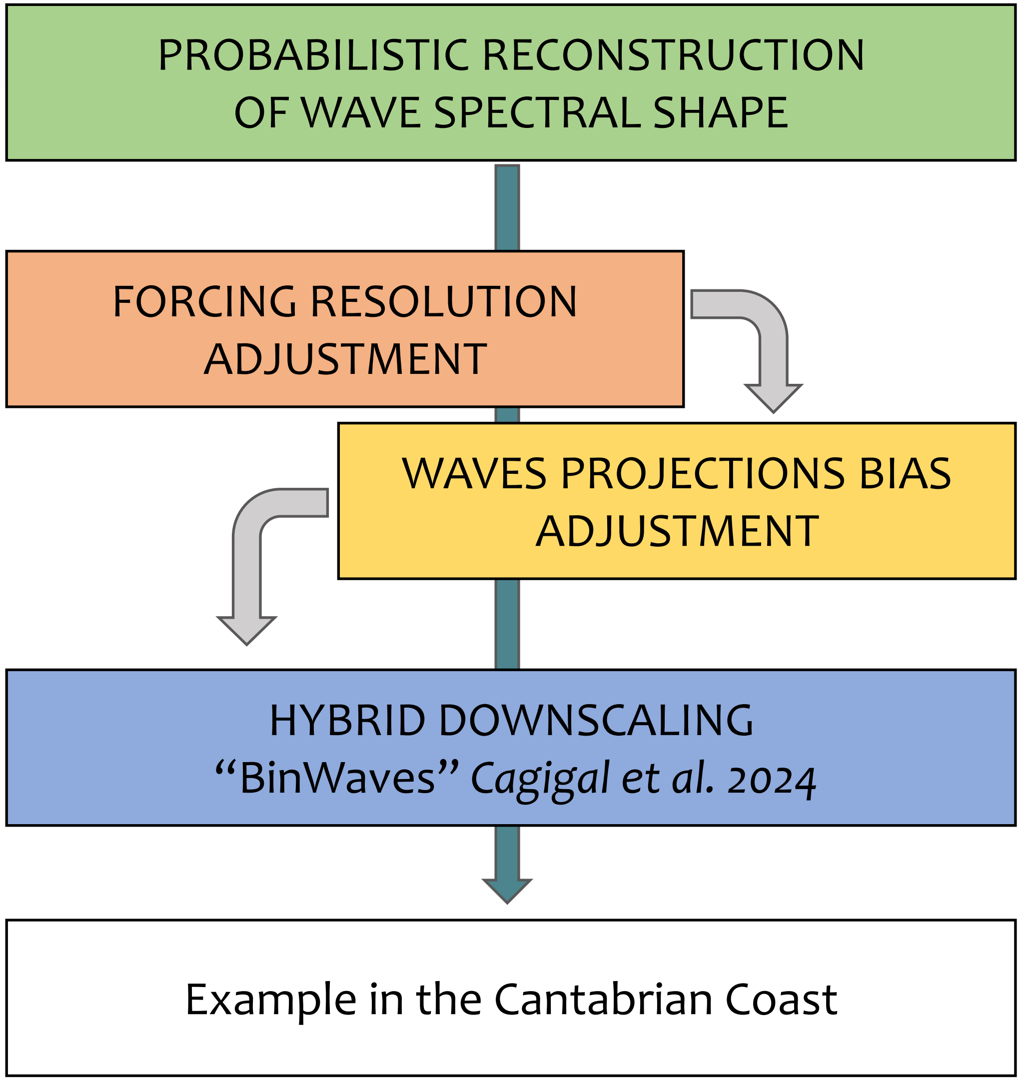
140 Years of Global Ocean Wind-Wave Climate Derived from CMIP6 ACCESS-CM2 and EC-Earth3 GCMs: Global Trends, Regional Changes, and Future Projections

Alberto Meucci,[a] Ian R. Young,[a] Mark Hemer,[b] Claire Trenham,[c] and Ian G. Watterson[d]

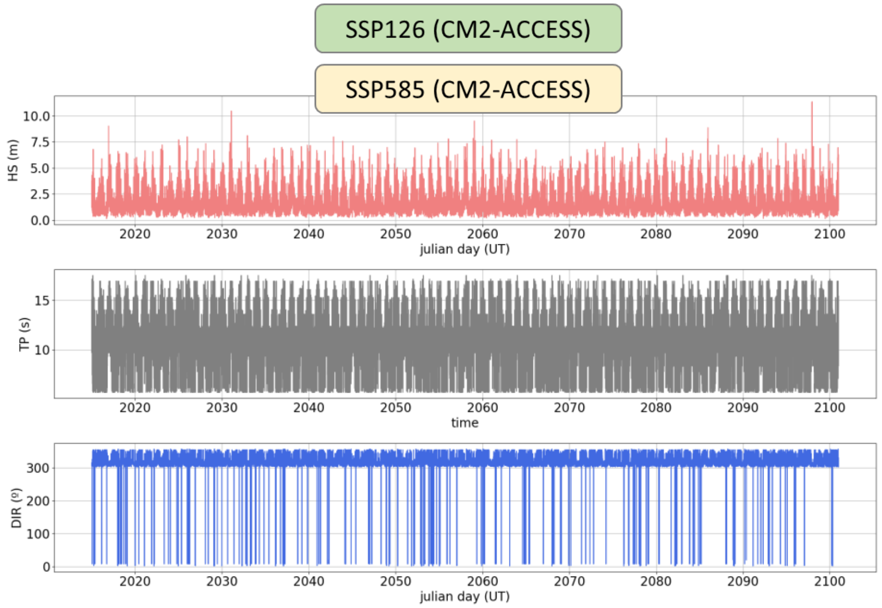
[a] Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria, Australia
[b] CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia
[c] CSIRO Oceans and Atmosphere, Canberra, Australian Capital Territory, Australia
[d] CSIRO Climate Science Centre, Aspendale, Victoria, Australia

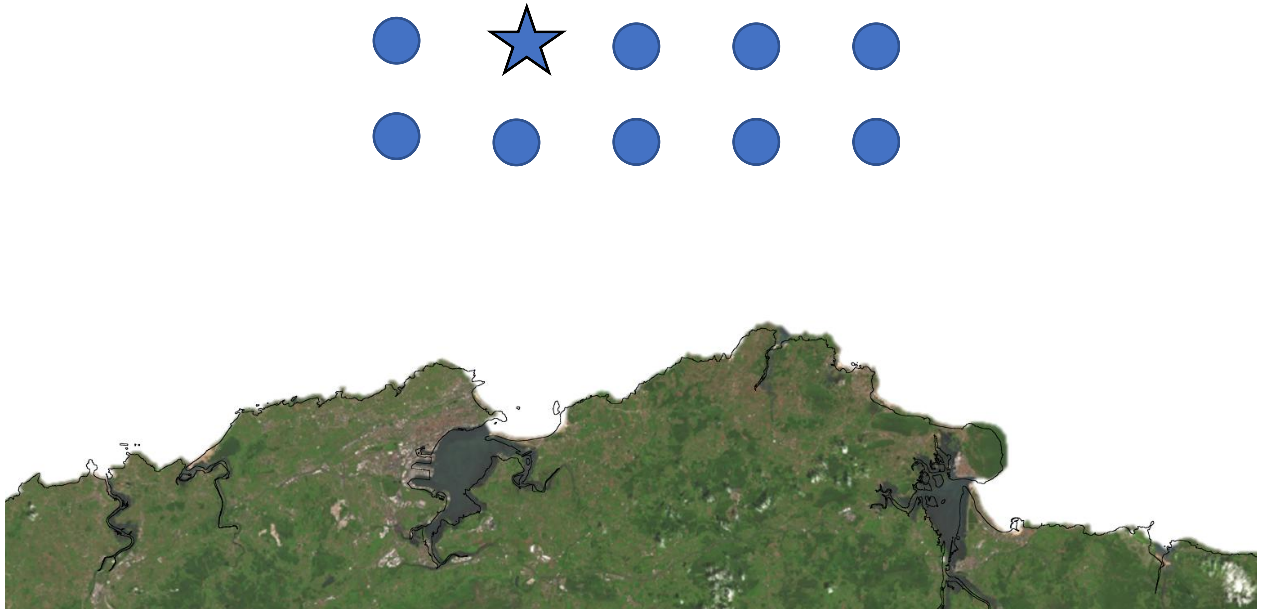
(Manuscript received 2 December 2021, in final form 8 November 2022)

Integral parameters	H_s	θ_p
	U_{10}	$T_{m,02}$
	f_p	$pH_{s,0}$, $pH_{s,1}$, $pH_{s,2}$
	$\bar{\theta}$	cge
Directional spectra	$10° \times 10°$ global grid	
	Australian climate ring	
	Victorian (AU) climate ring	

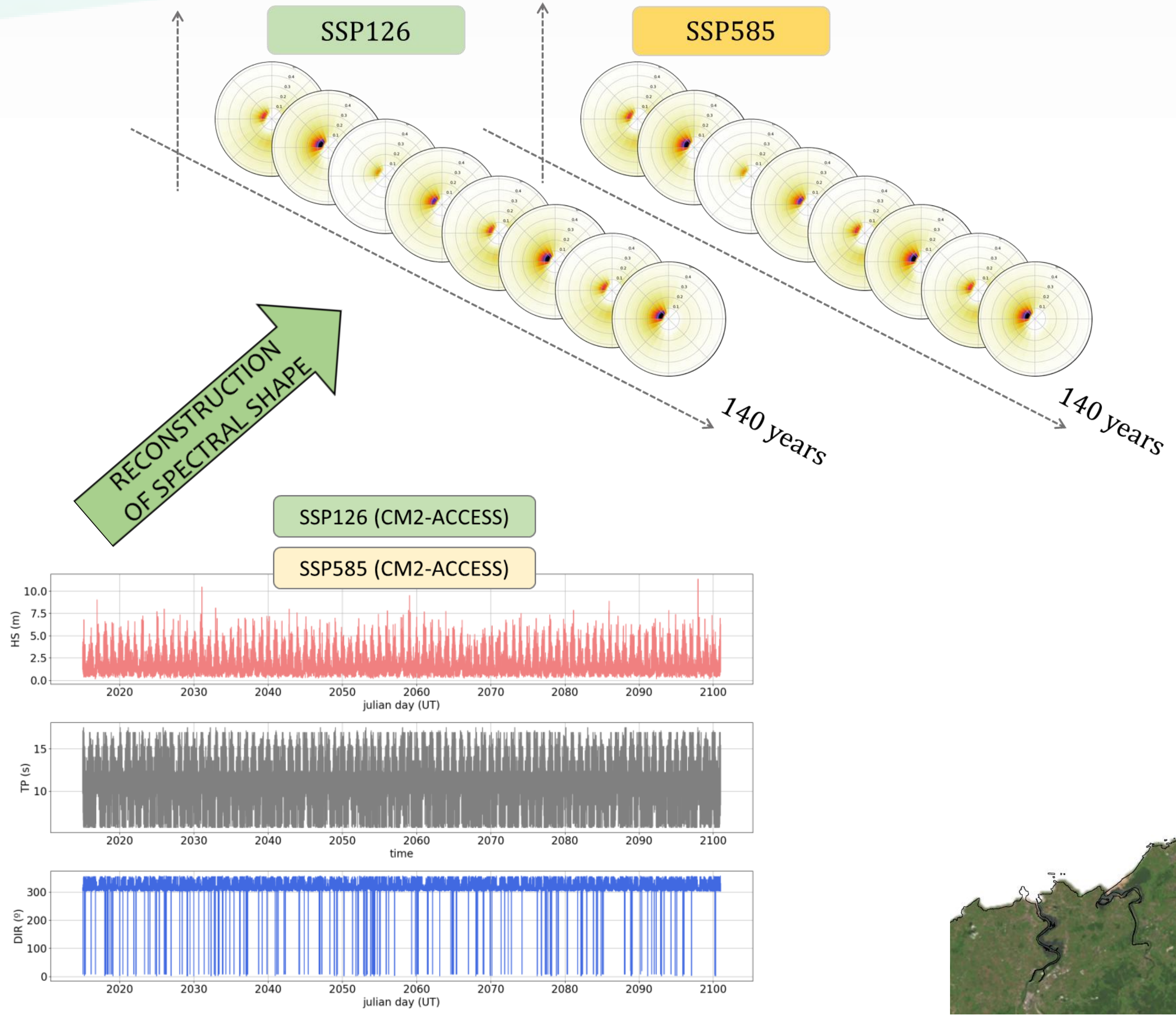


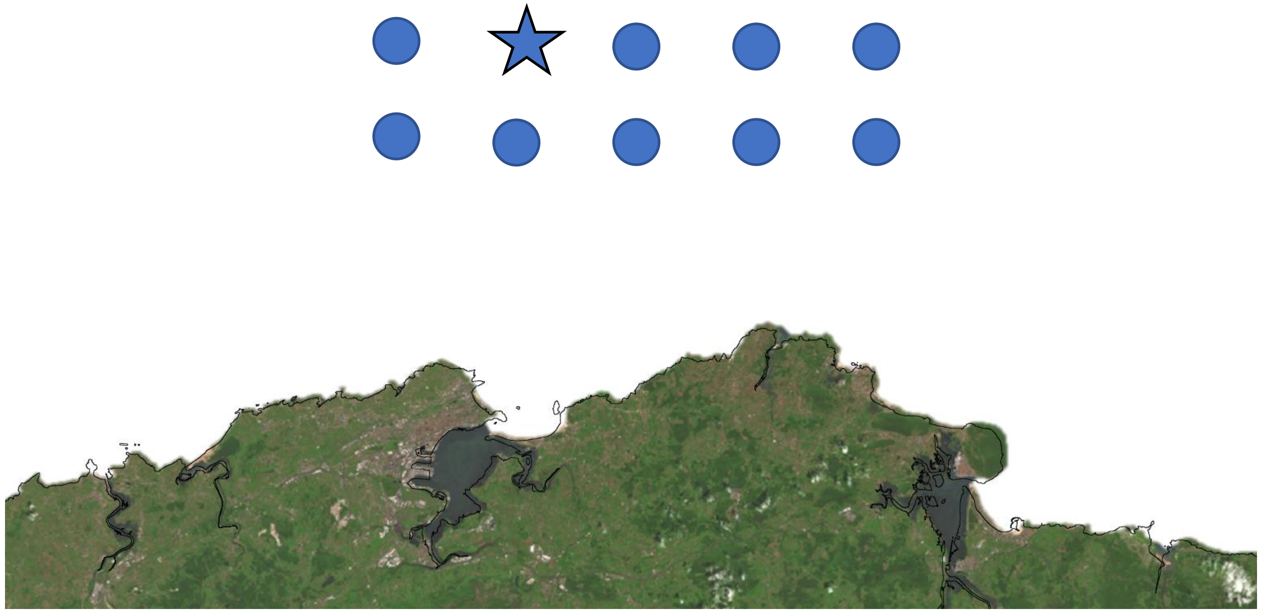
3. Example in the Cantabrian coast





3. Example in the Cantabrian coast

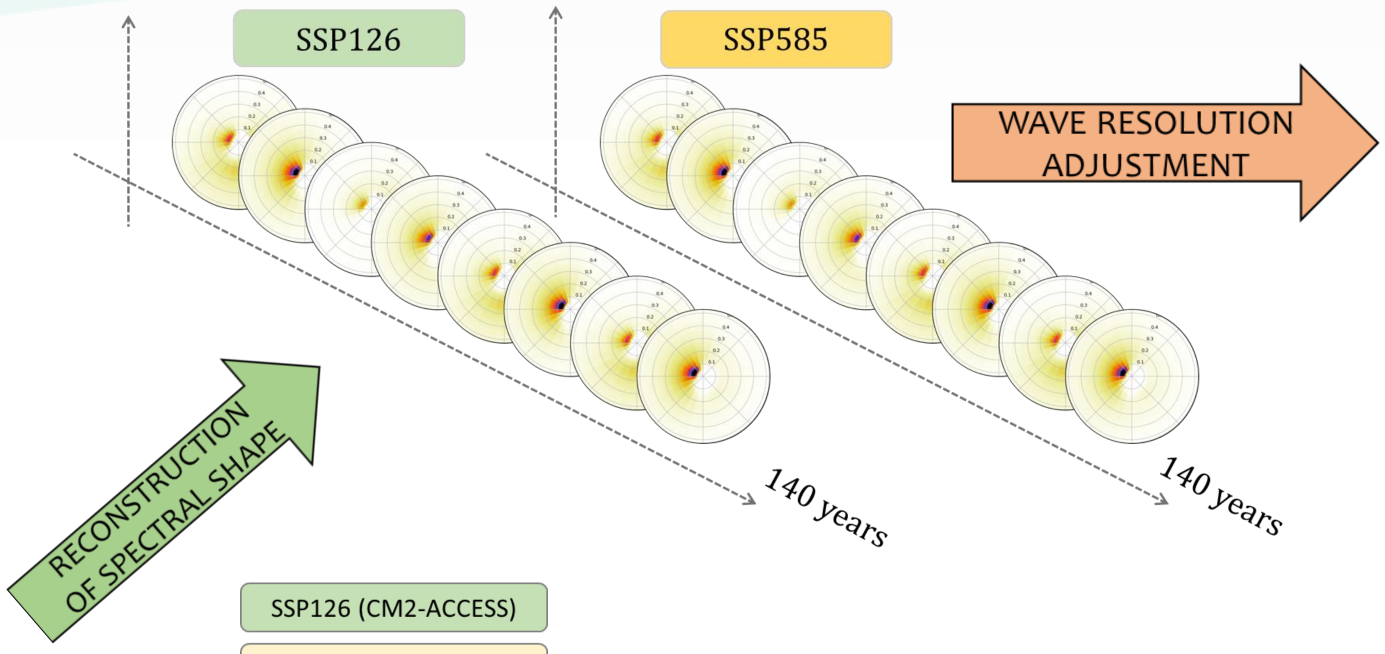


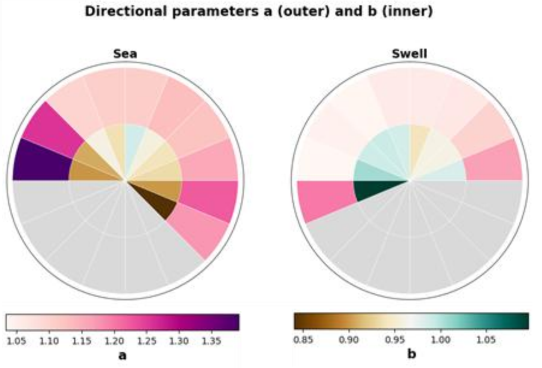


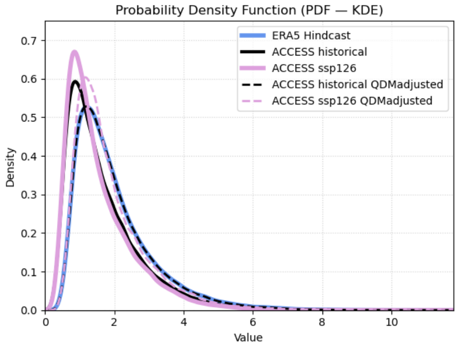
3. Example in the Cantabrian coast

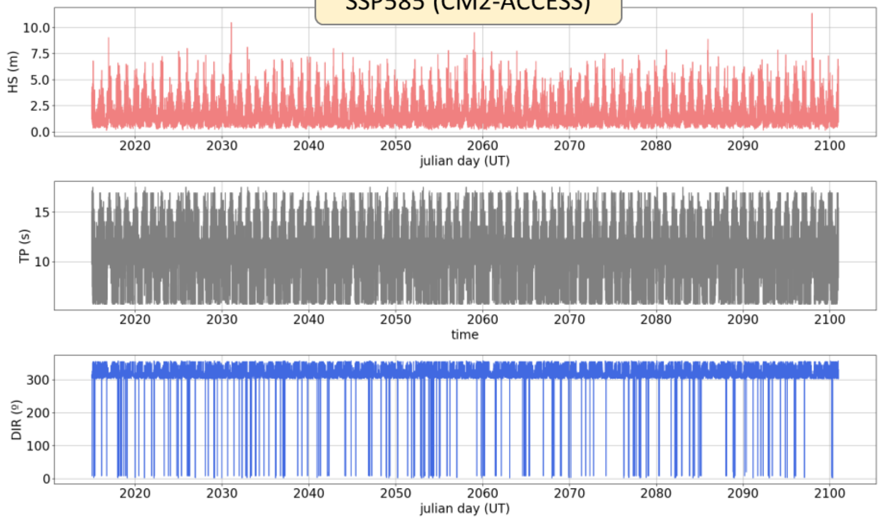
UC | Universidad de Cantabria

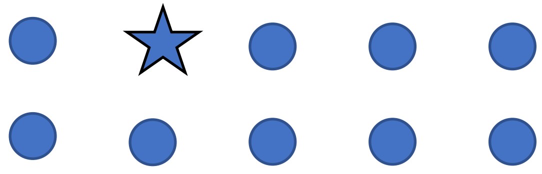
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA



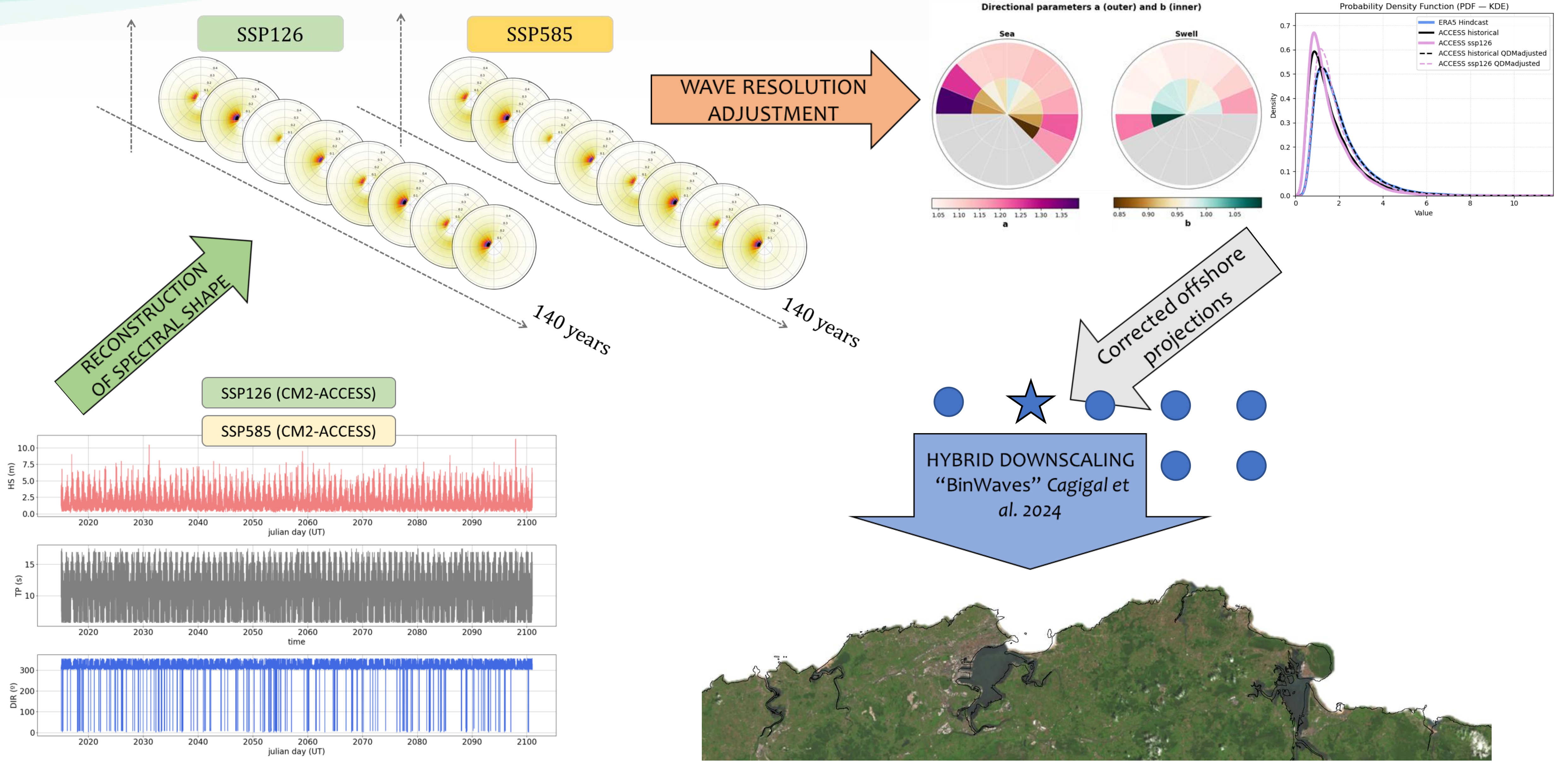








3. Example in the Cantabrian coast



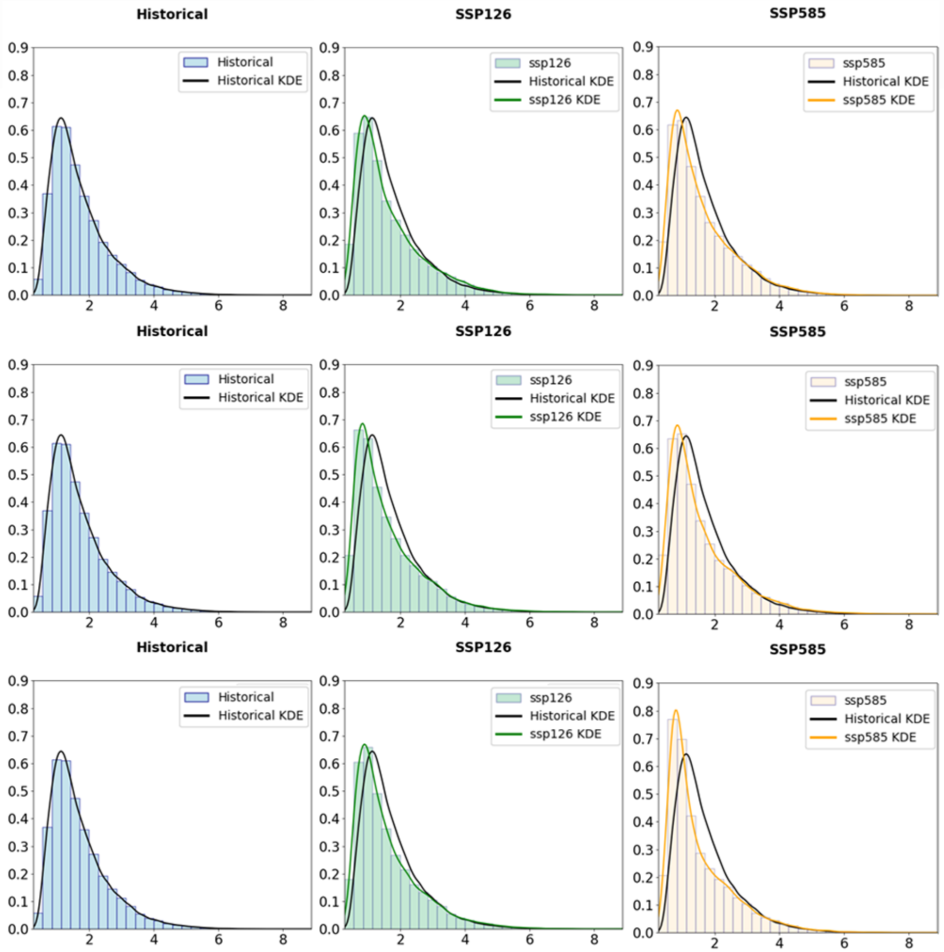
3. Example in the Cantabrian coast

Universidad de Cantabria
Geomatics and Ocean Engineering Group
UNIVERSIDAD DE CANTABRIA

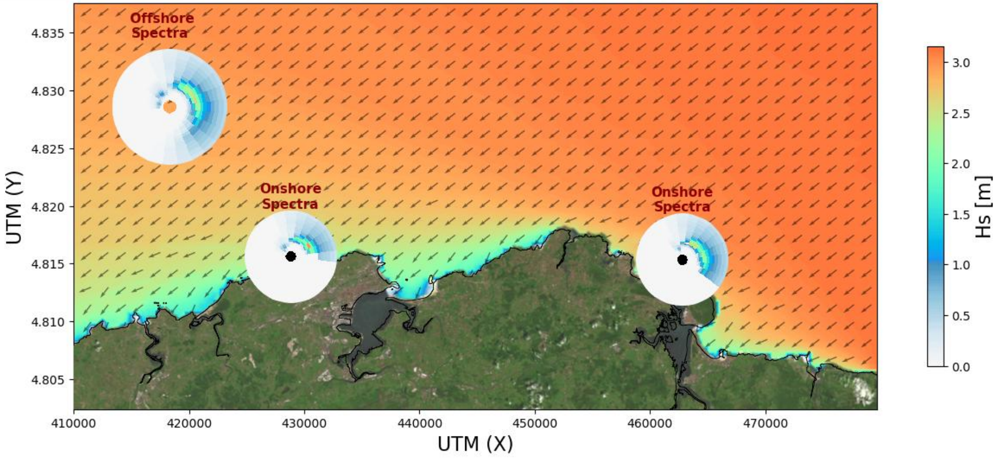
Near term
2021-2040

Mid term
2041-2060

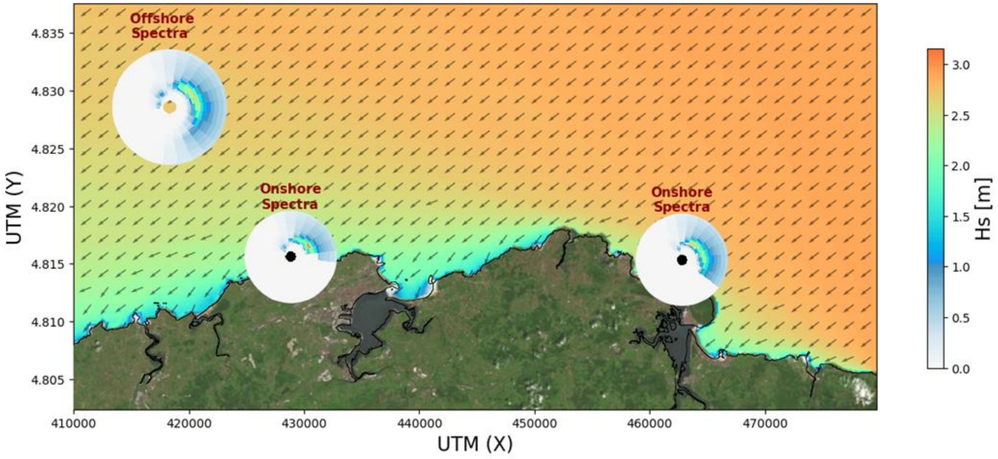
Long term
2081-2100



SSP126 (CM2-ACCESS)



SSP585 (CM2-ACCESS)



Acknowledgments

This work has been partially funded by the projects:

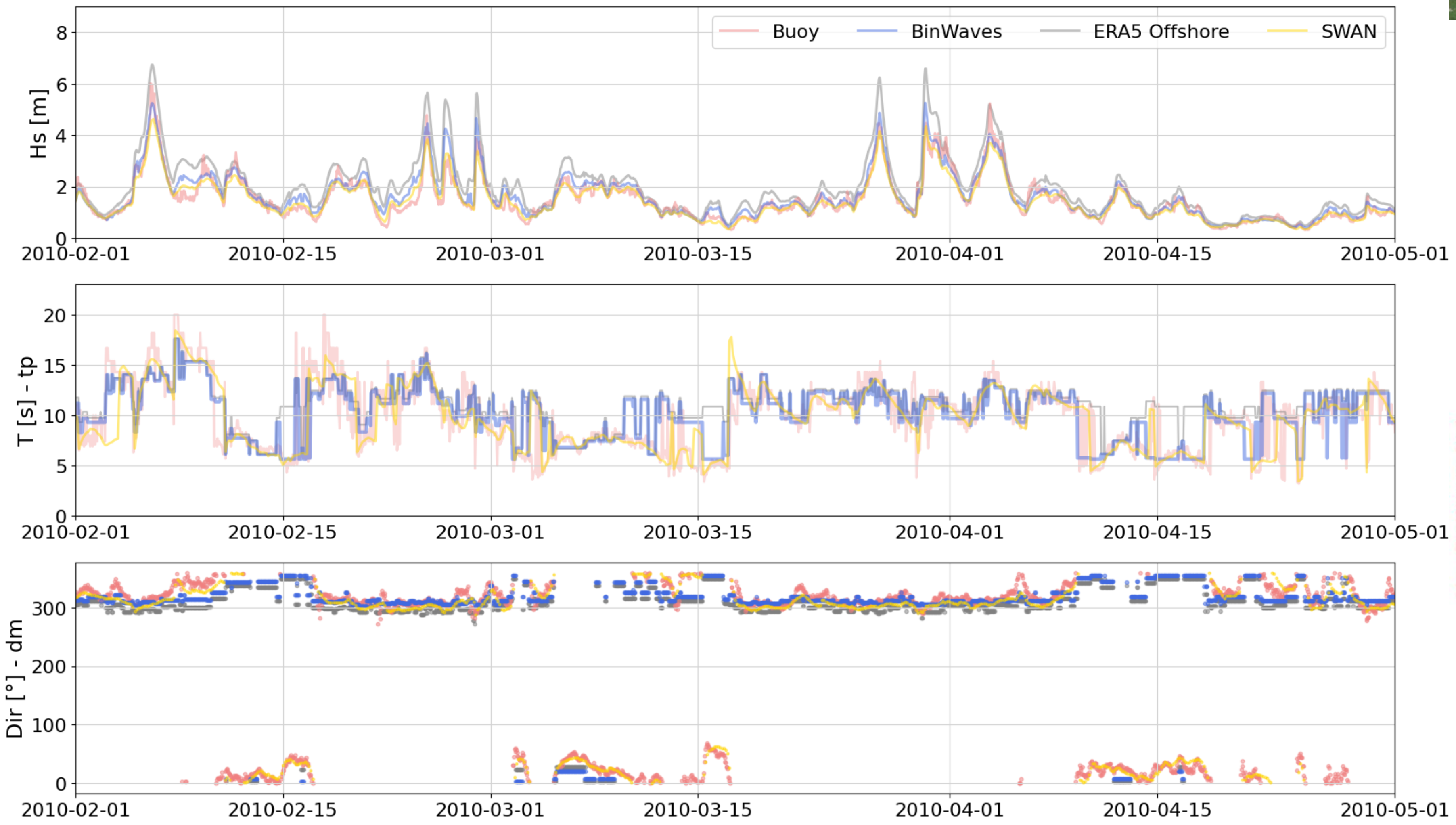
MyFlood (PLEC2022-009362 - MCIN/AEI/10.13039/501100011033 and European Union Next GenerationEU/PRTR)
HyBay (PID2022-141181OB-I00, MCIN/AEI/10.13039/501100011033/FEDER, EU)
PerfectStorm (2023/TCN/003 - Government of Cantabria/FEDER, EU).

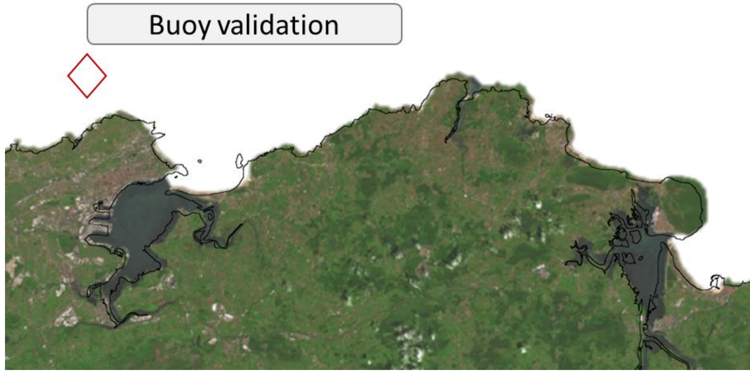
Thanks for your attention…

Gabriel Bellido
bellidog@unican.es

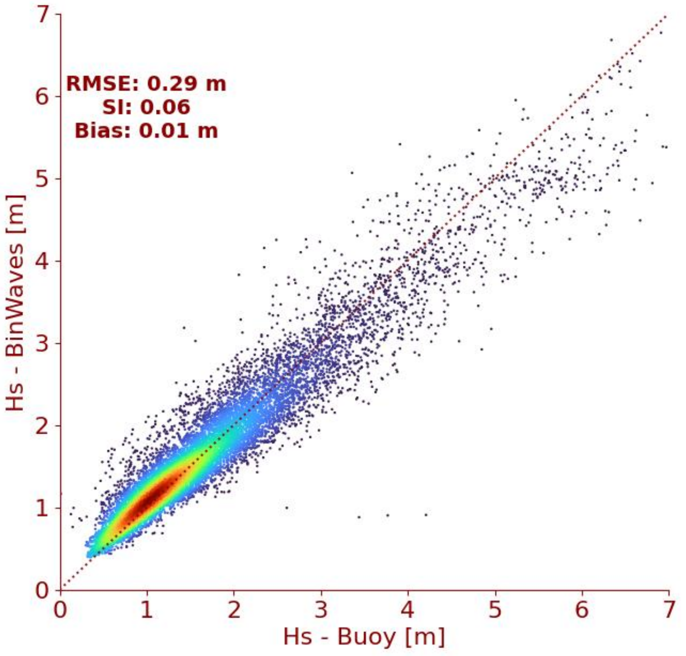
Hybrid downscaling to the Cantabrian coast

Buoy validation





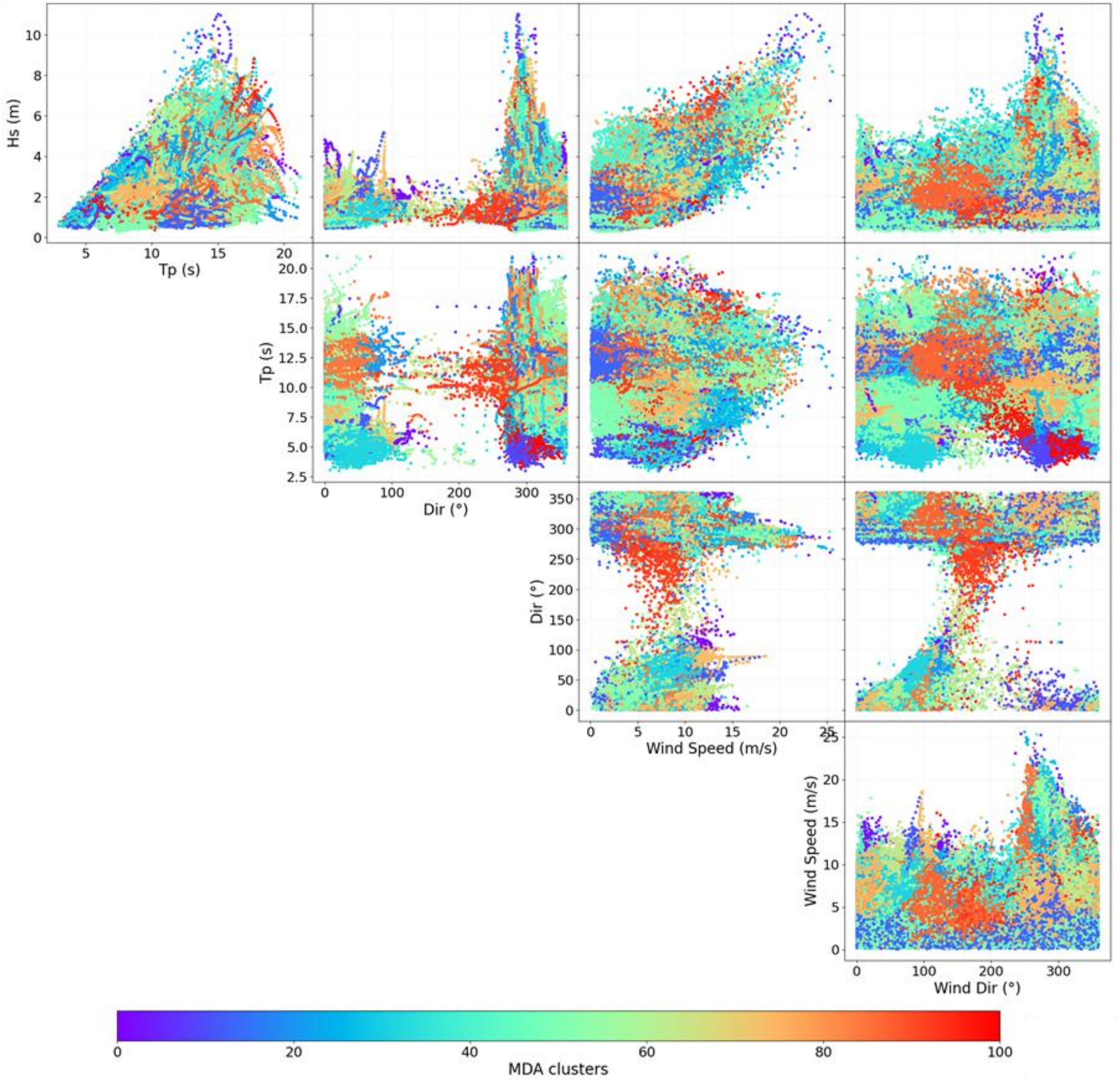
Buoy validation

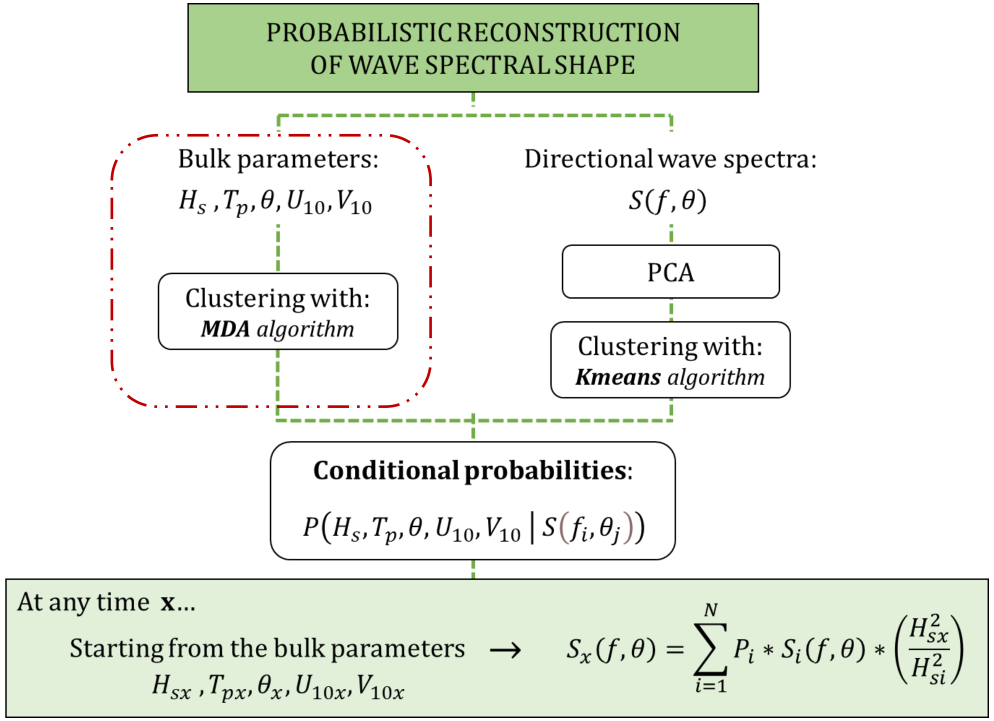


1. From Bulk Parameters to Spectra

Clustering **Bulk parameters:**

100 clusters

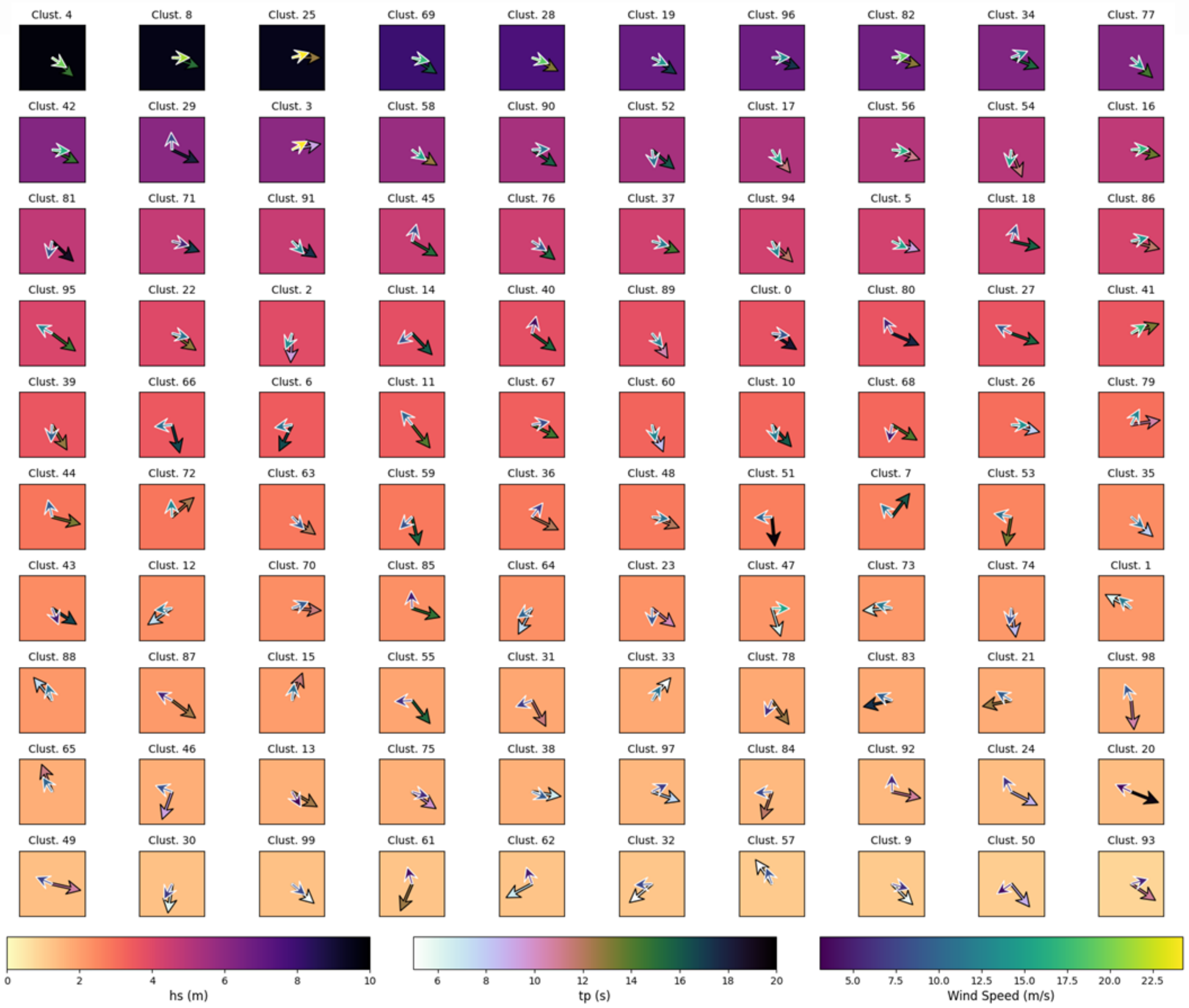


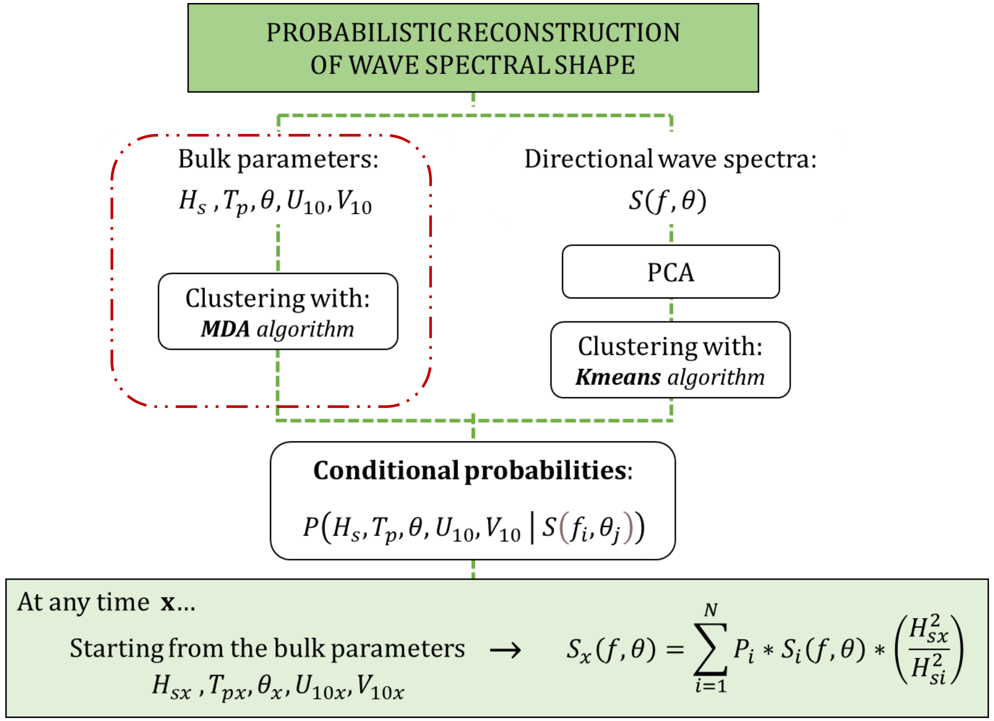


1. From Bulk Parameters to Spectra

Clustering **Bulk parameters:**

100 clusters

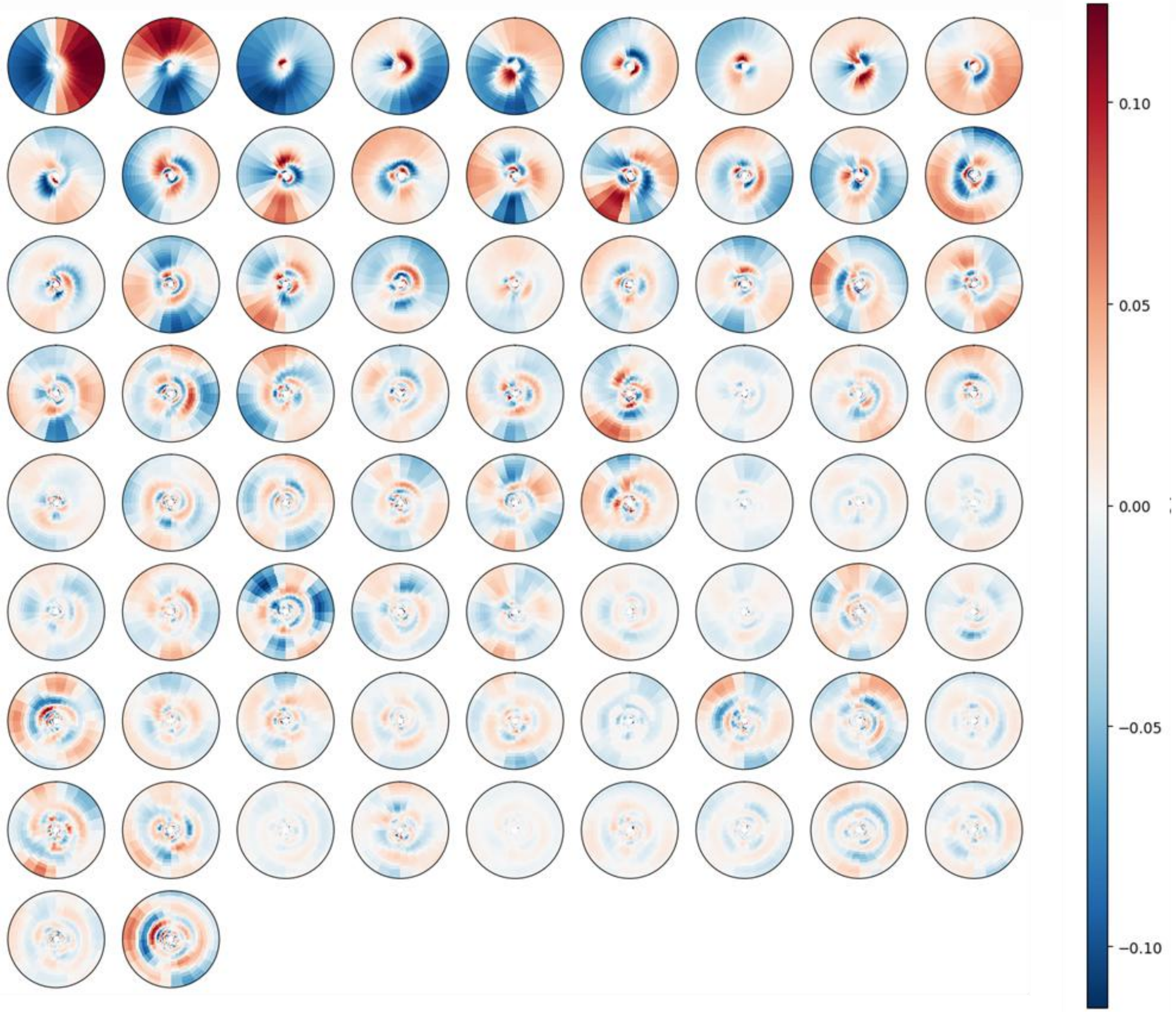


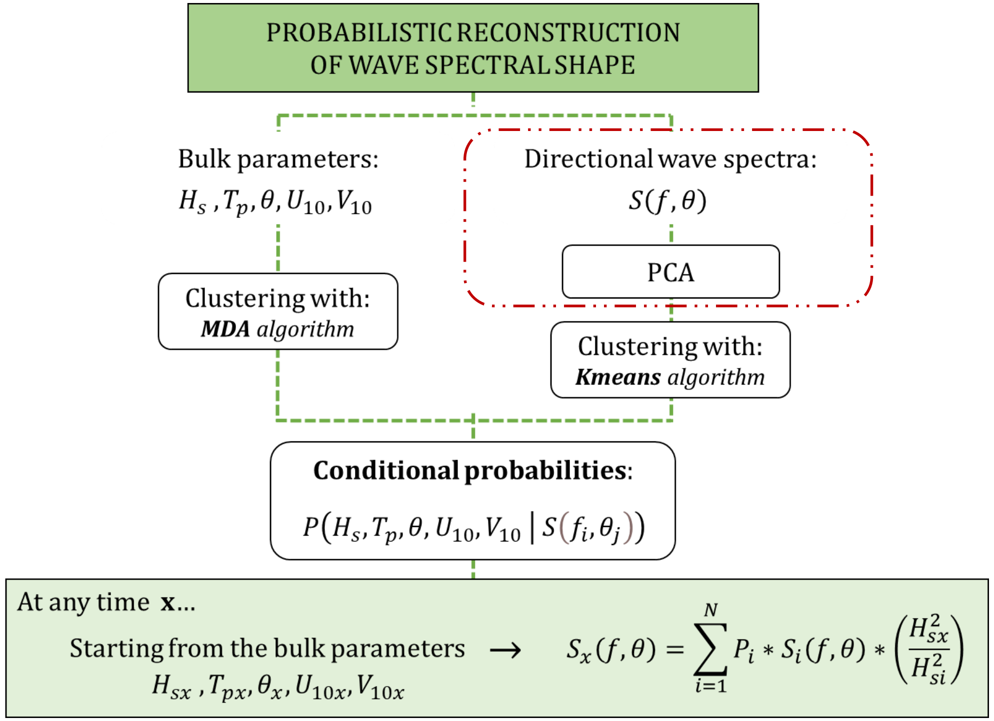


1. From Bulk Parameters to Spectra

Clustering **Directional Wave Spectra:**

- 74 PCs
- 95% variance explained





1. From Bulk Parameters to Spectra

Clustering **Directional Wave Spectra:** 81 clusters