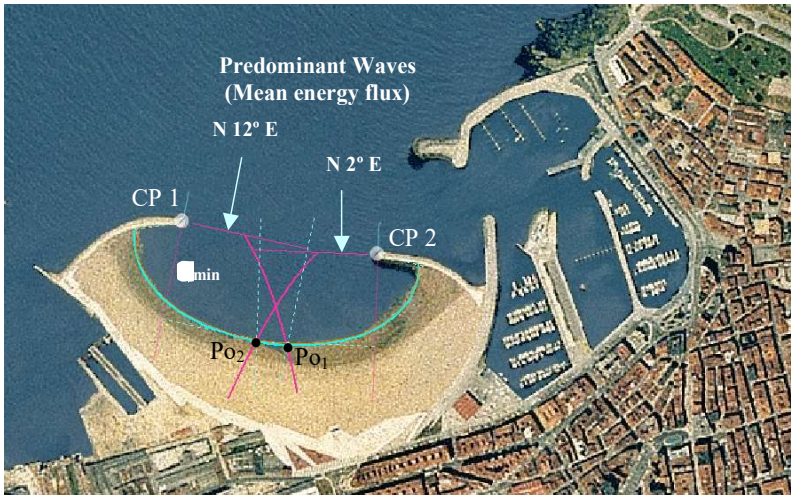
# Applications of data science in coastal engineering

**Paula Camus**

MASCOT-NUM 2021

28TH-30TH April

How is the beach equilibrium planform?

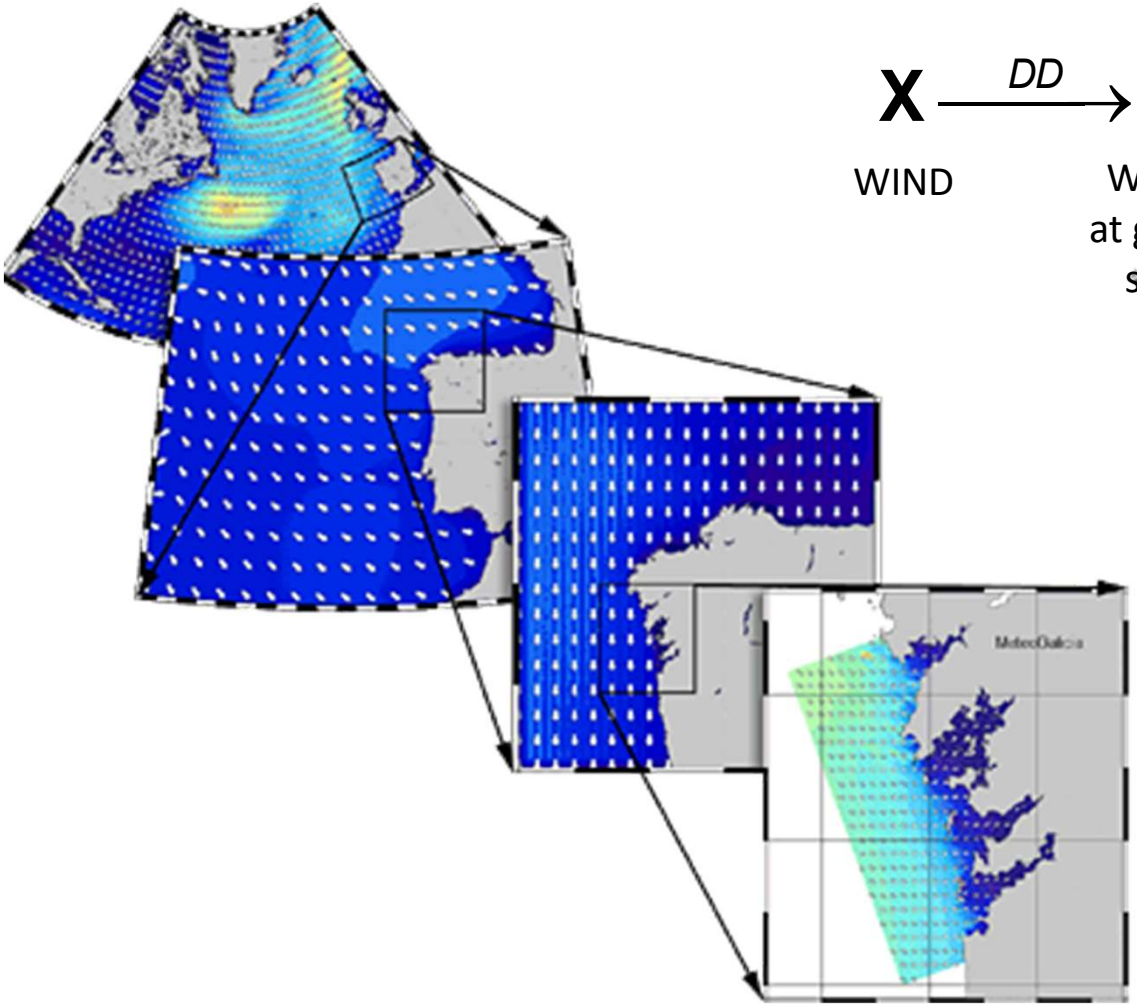



How estimate the longitudinal sediment transport?


Which is the block size of this breakwater?

How many hours/year is the agitation of this port over 30 cm?

# Propagation of wave climate to coastal areas



$$\mathbf{X} \xrightarrow{DD} \mathbf{Y}_1 \xrightarrow{DD} \mathbf{Y}_2 \xrightarrow{DD} \mathbf{Y}_3$$

WIND

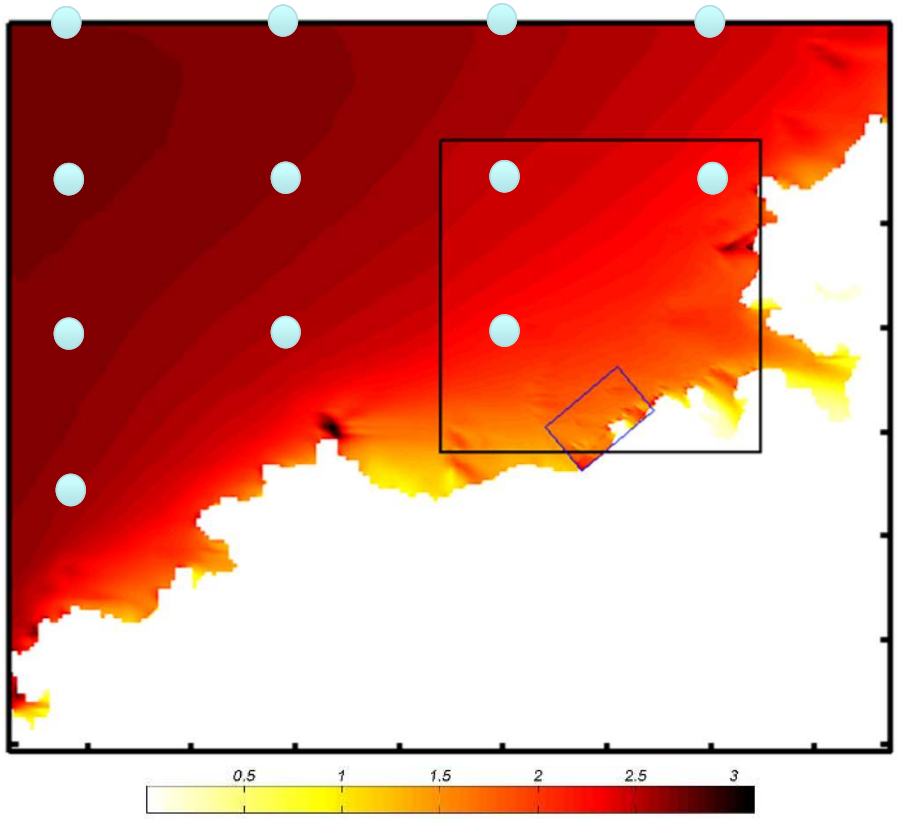
WAVES at global scale

WAVES at regional scale

WAVES at local scale

# Wave transformation processes in shallow water

# Approaches to transfer regional wave climate to coastal areas




## Dynamical Downscaling

Rusu et al., 2008

## Statistical Downscaling

Kalra et al., 2005
Browne et al., 2007

## Hybrid Downscaling

Groeneweg et al., 2006
Stansby et al., 2006
Breivik et al., 2009
Galiskova and Weisse, 2006
Herman et al. 2009

# Hybrid downscaling approach to propagate wave climate to coastal areas

1 **Data**

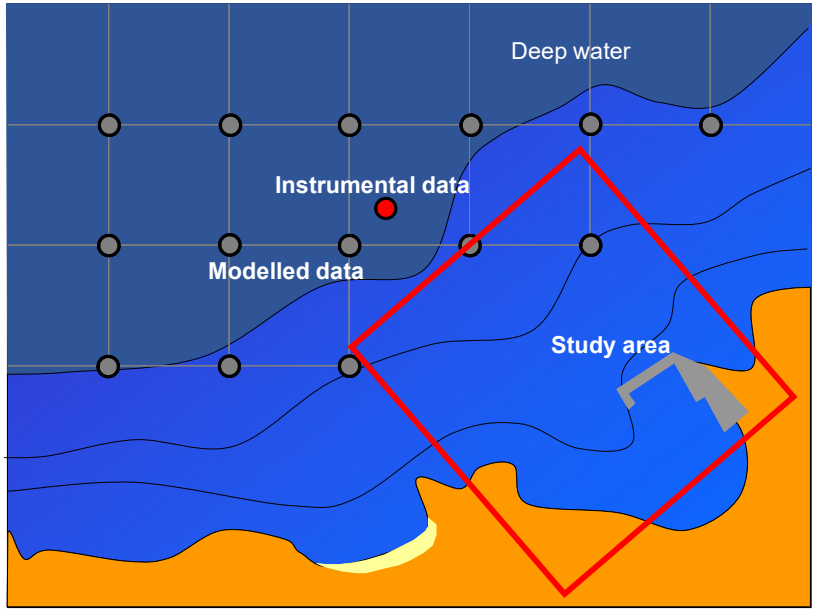
2 Calibration

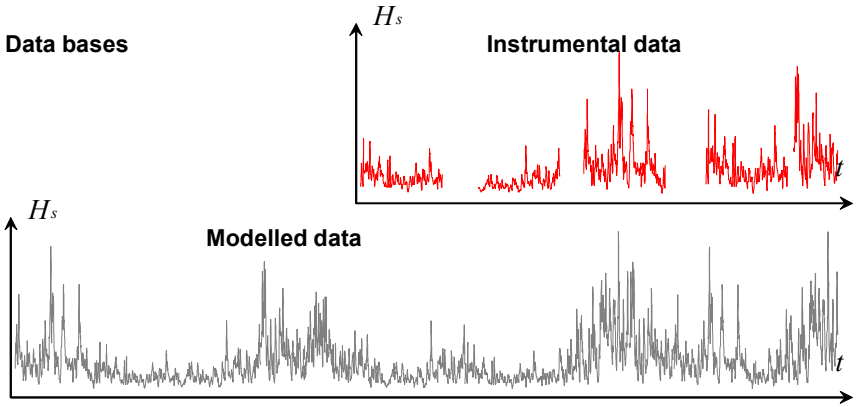
3 Selection

4 Propagation

5 Time series reconstruction

6 Marime climate



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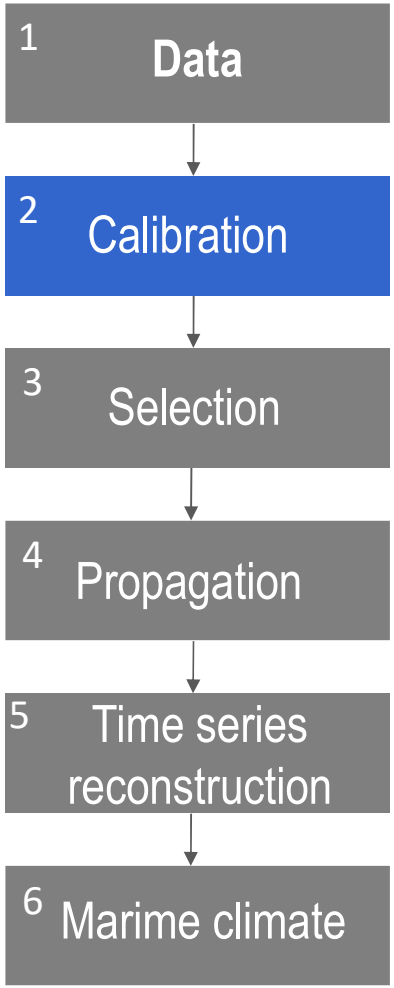


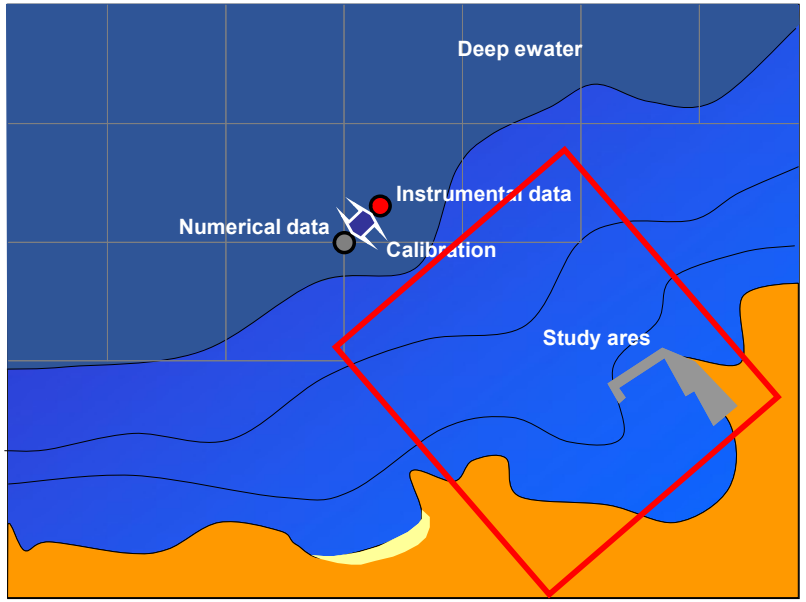


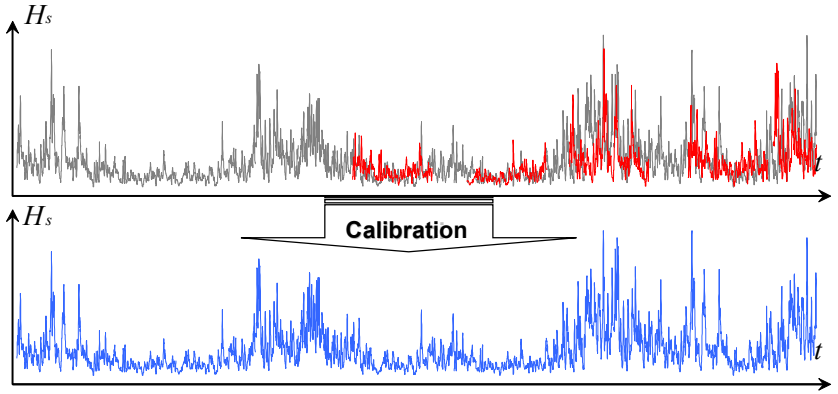

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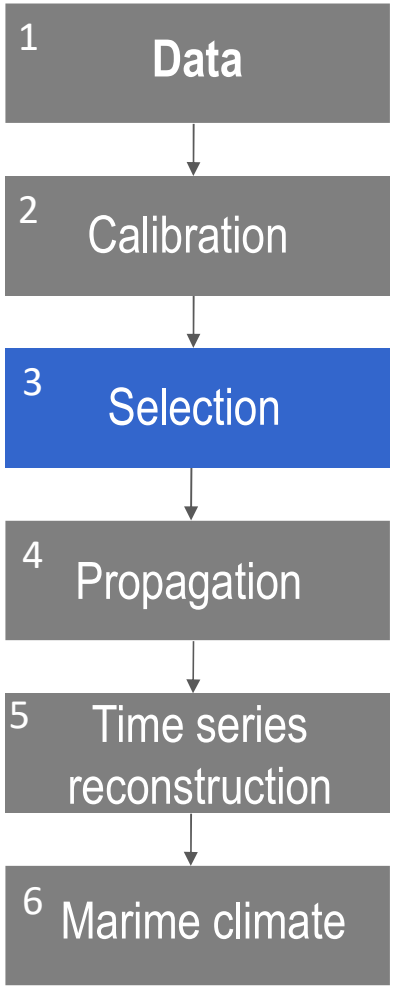


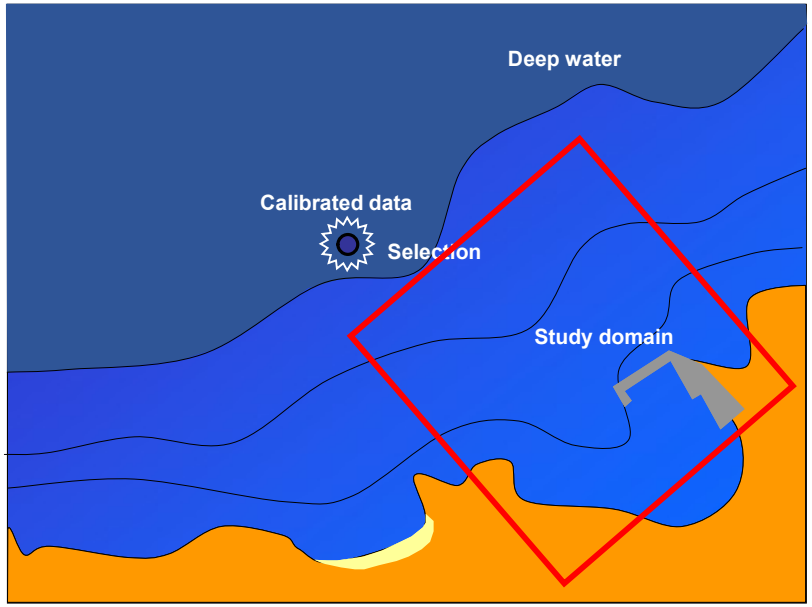


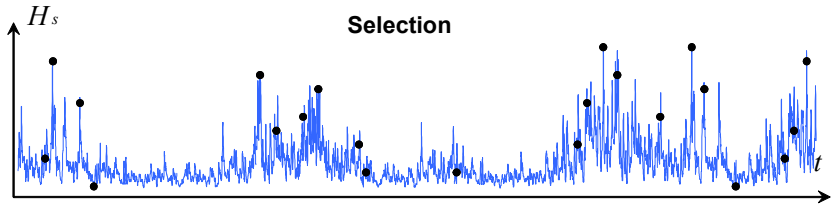

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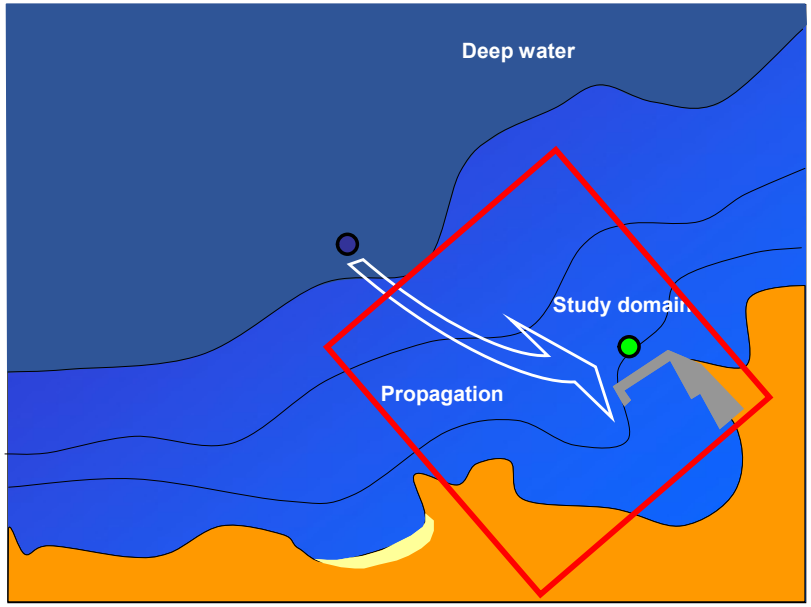


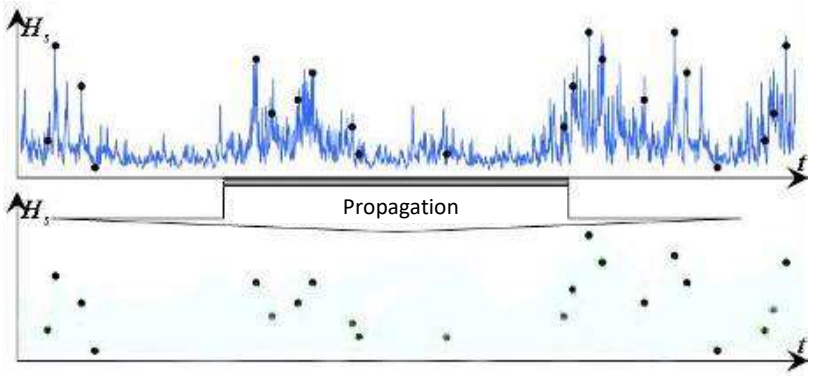


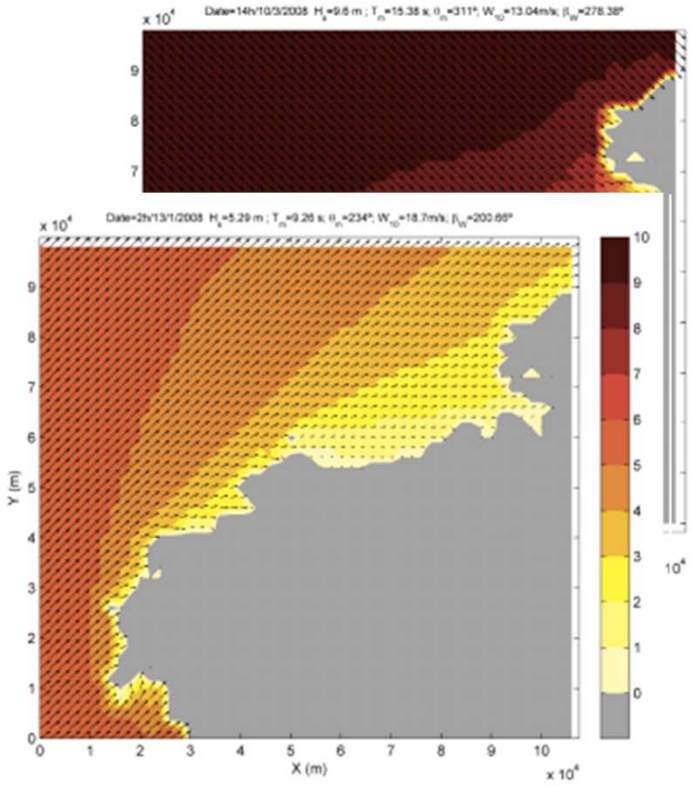

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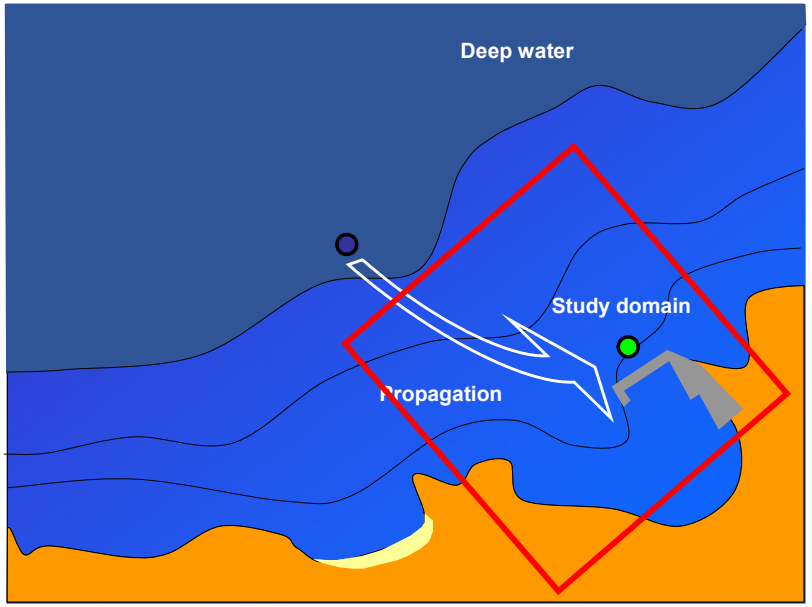


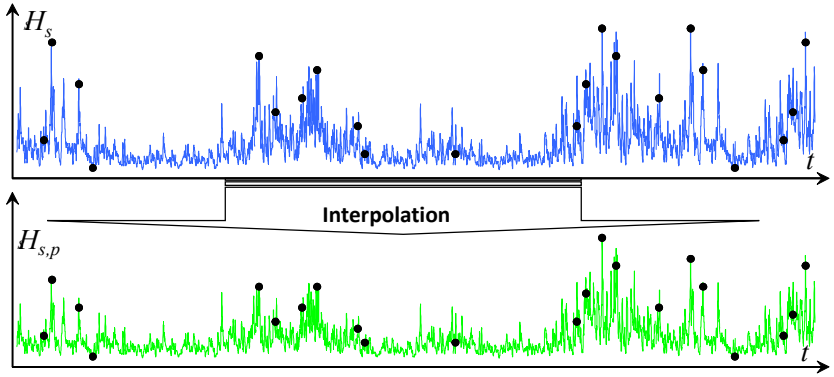

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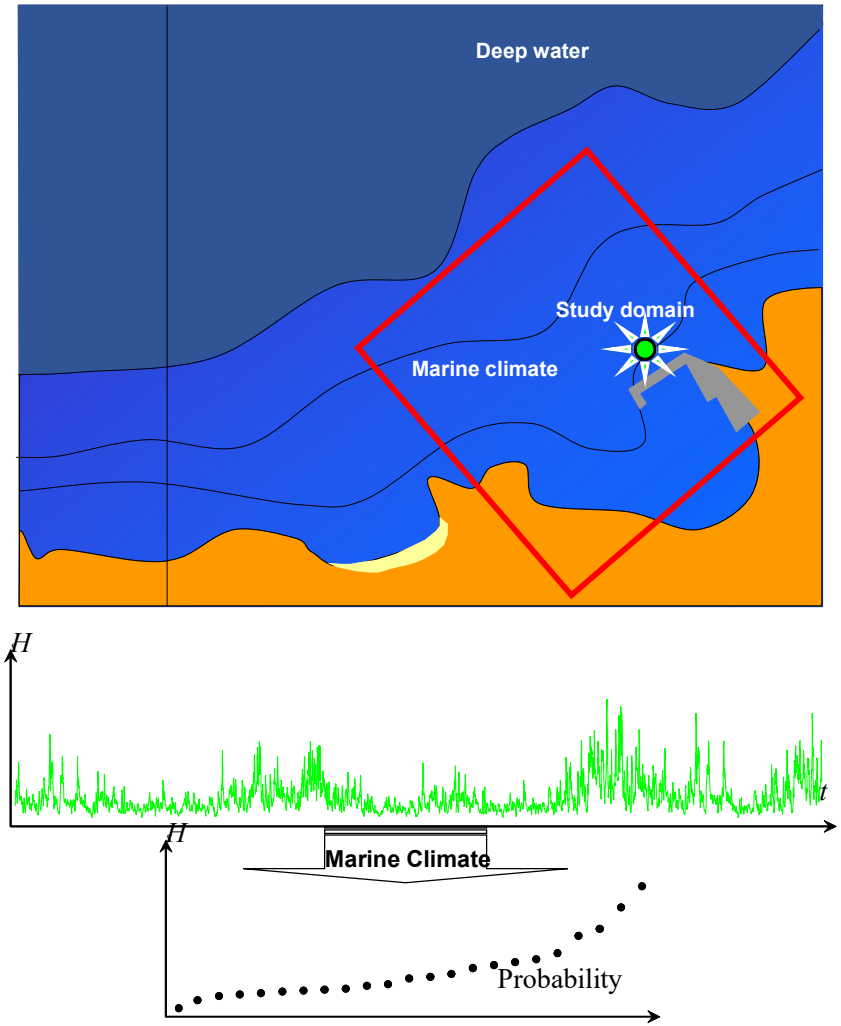

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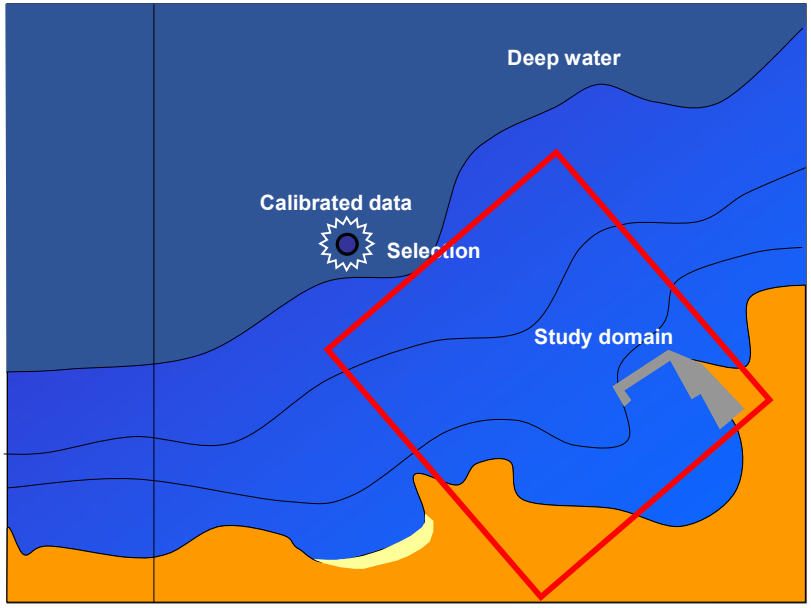
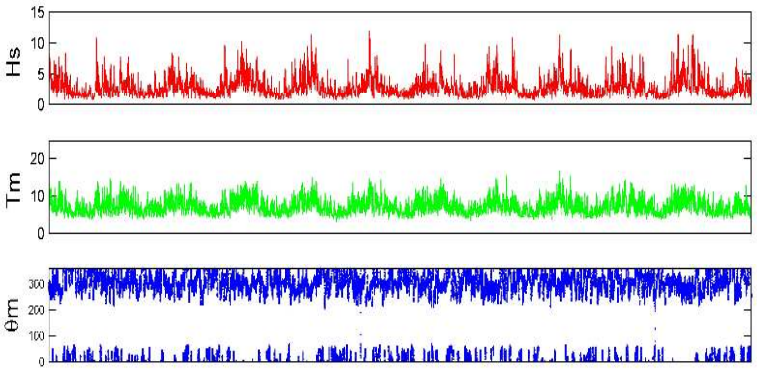
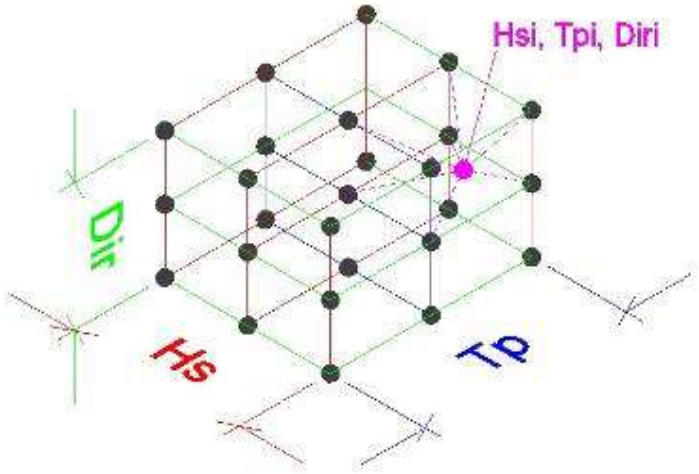
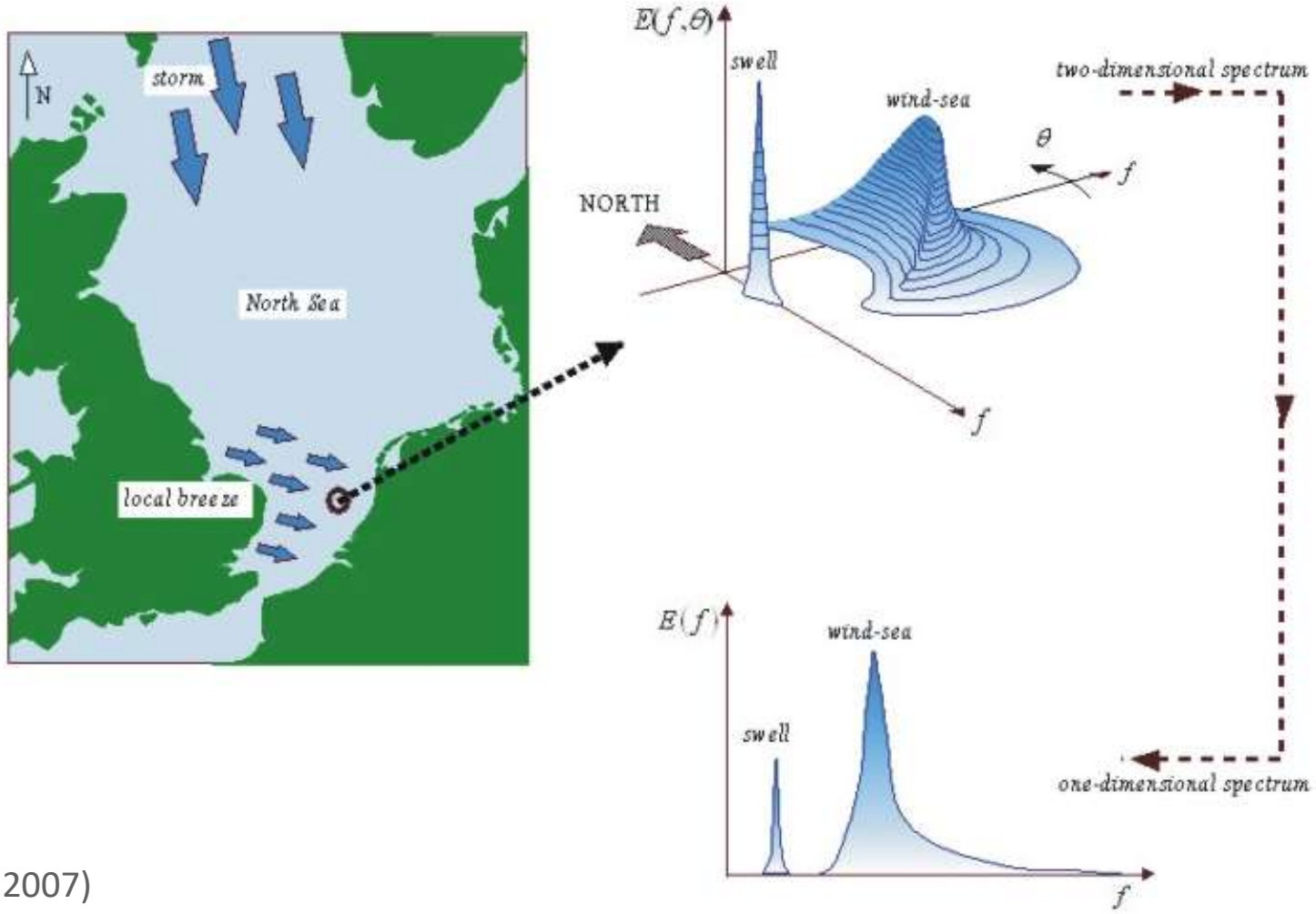



HIPERCUBE

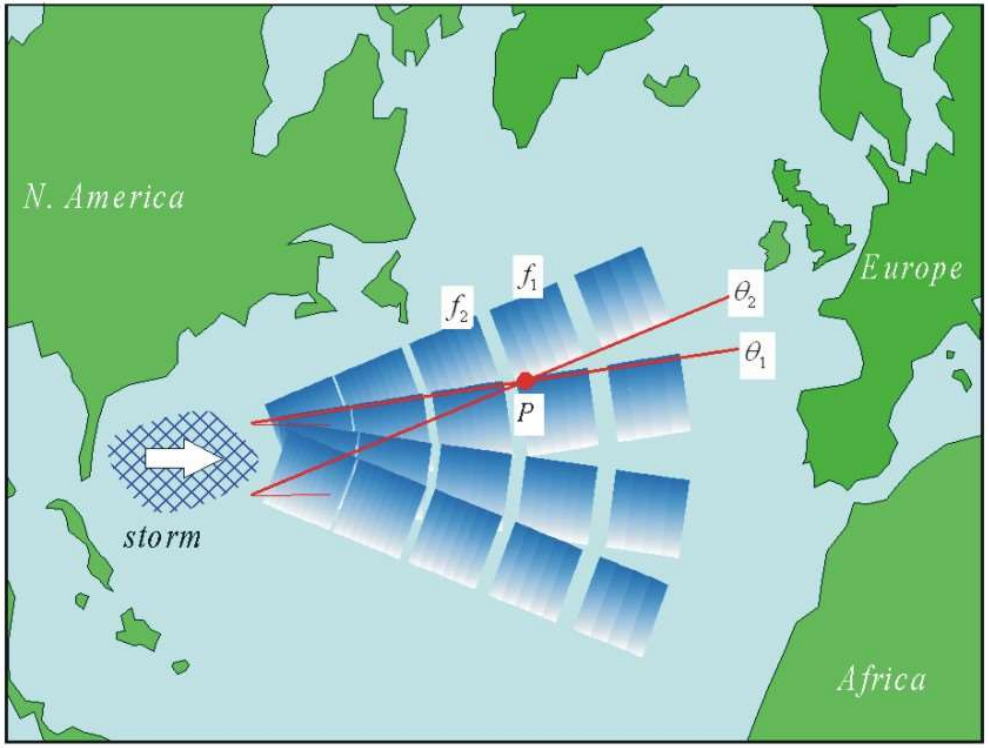


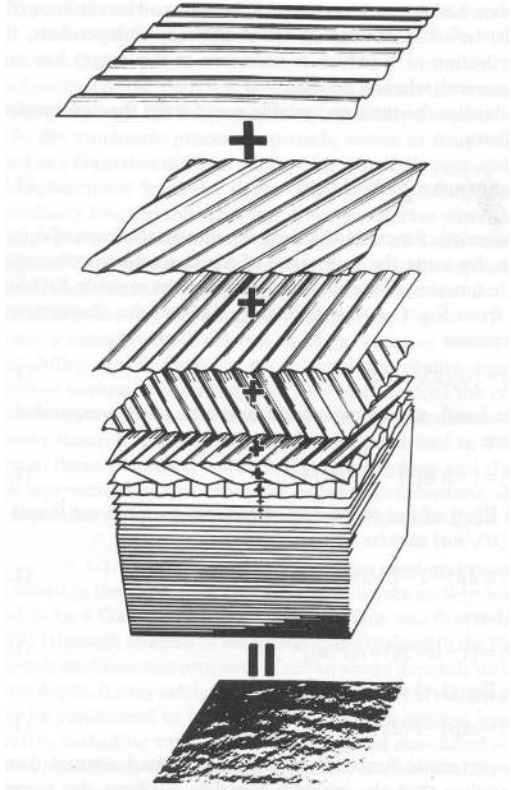
# Hybrid downscaling approach to propagate wave climate to coastal areas
# LIMITATIONS

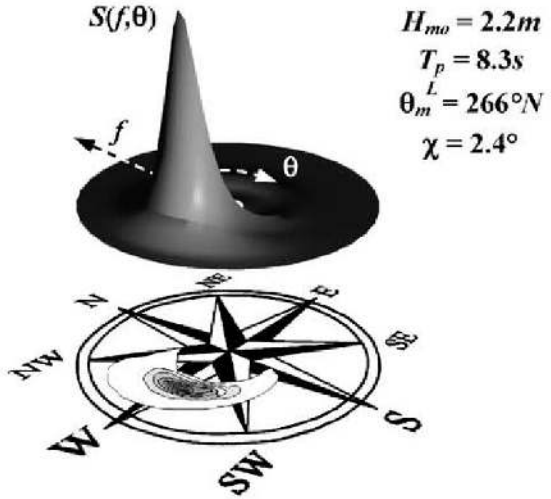


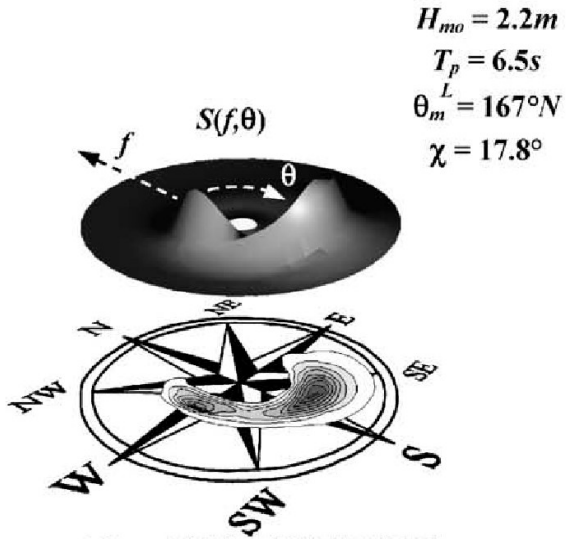

(Holthuijsen, 2007)

# Hybrid downscaling approach to propagate wave climate to coastal areas
# LIMITATIONS



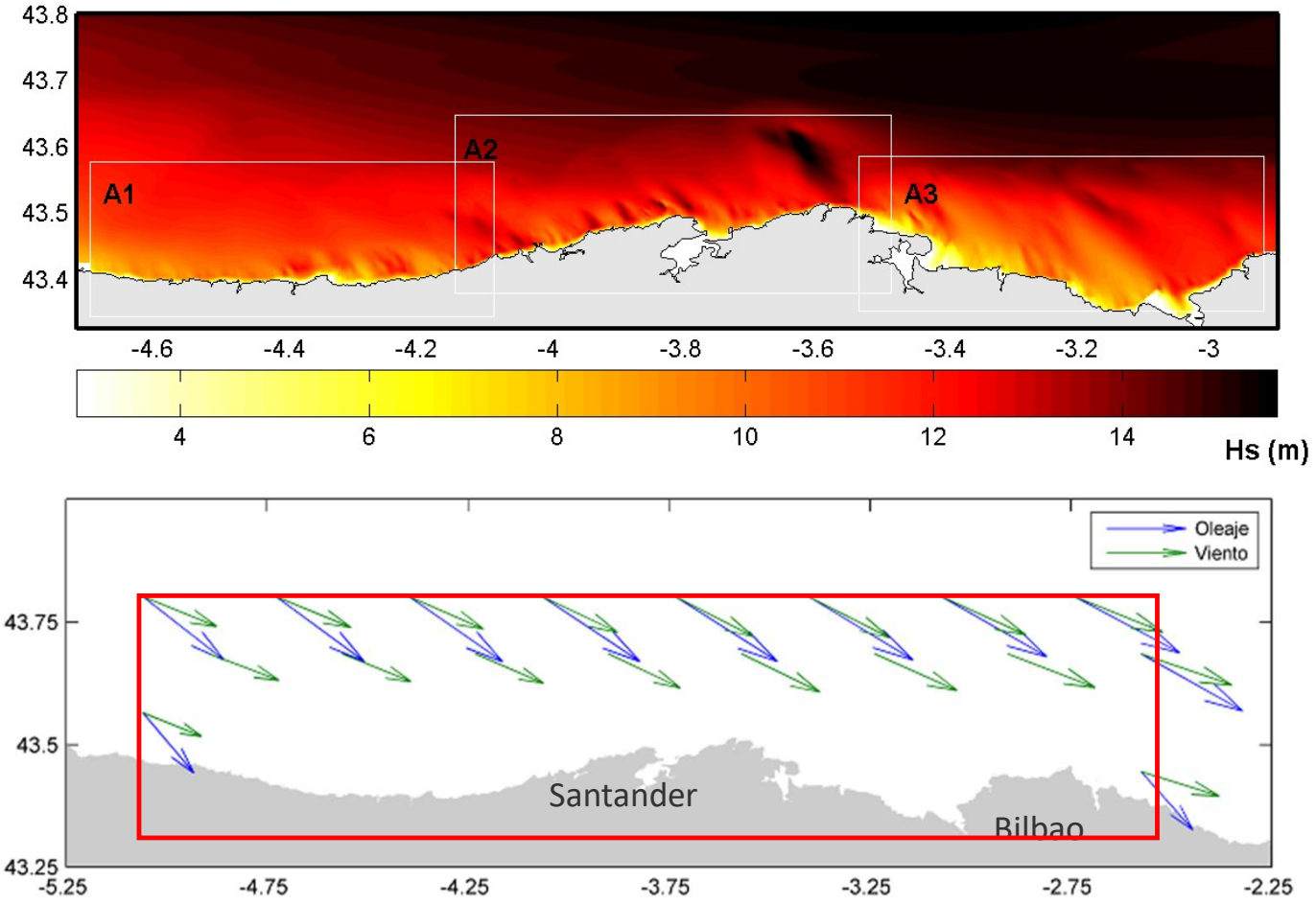





# Hybrid downscaling approach to propagate wave climate to coastal areas
# LIMITATIONS

## Wave variability along the coast



# Hybrid downscaling approach to propagate wave climate to coastal areas
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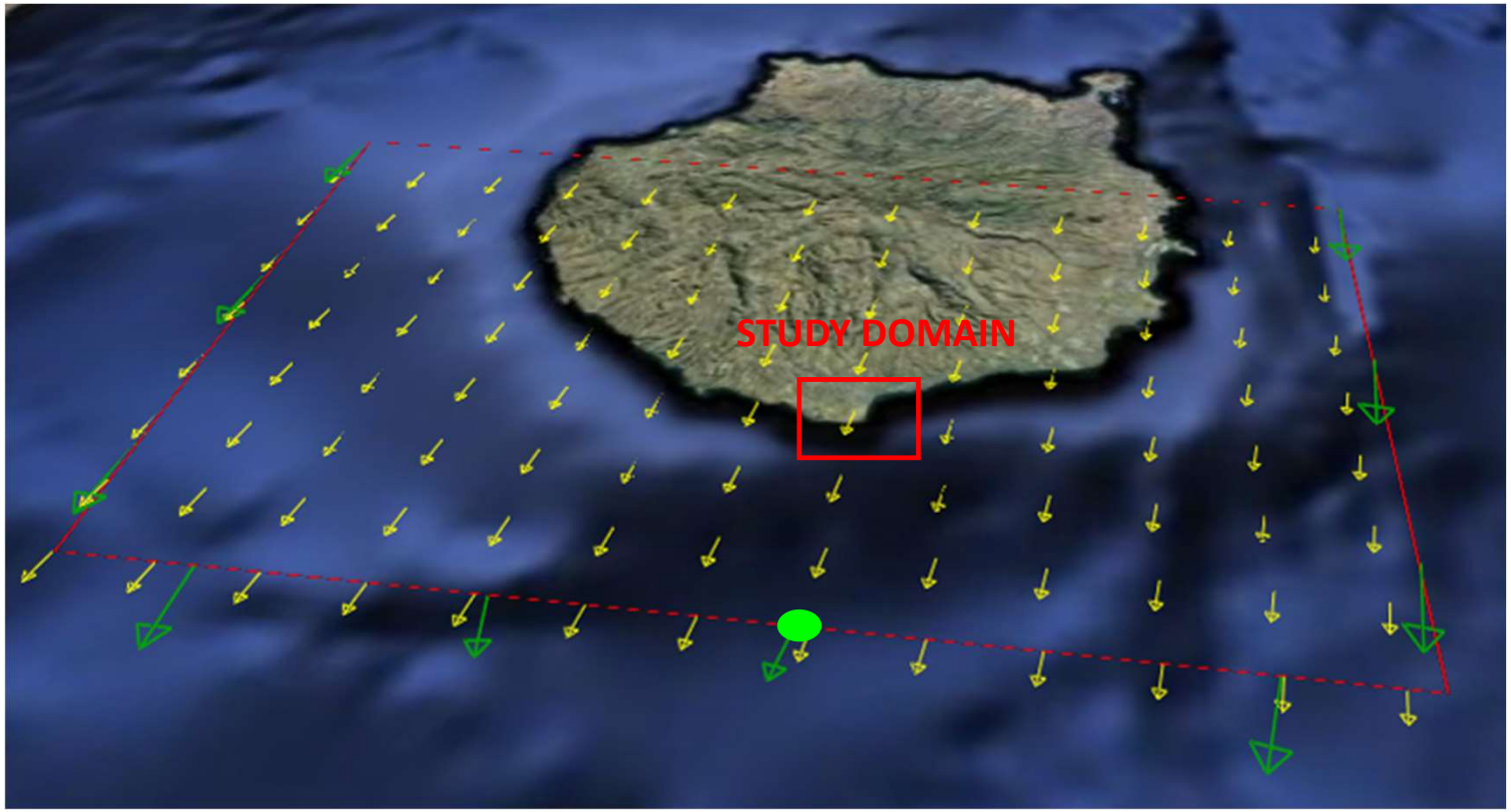
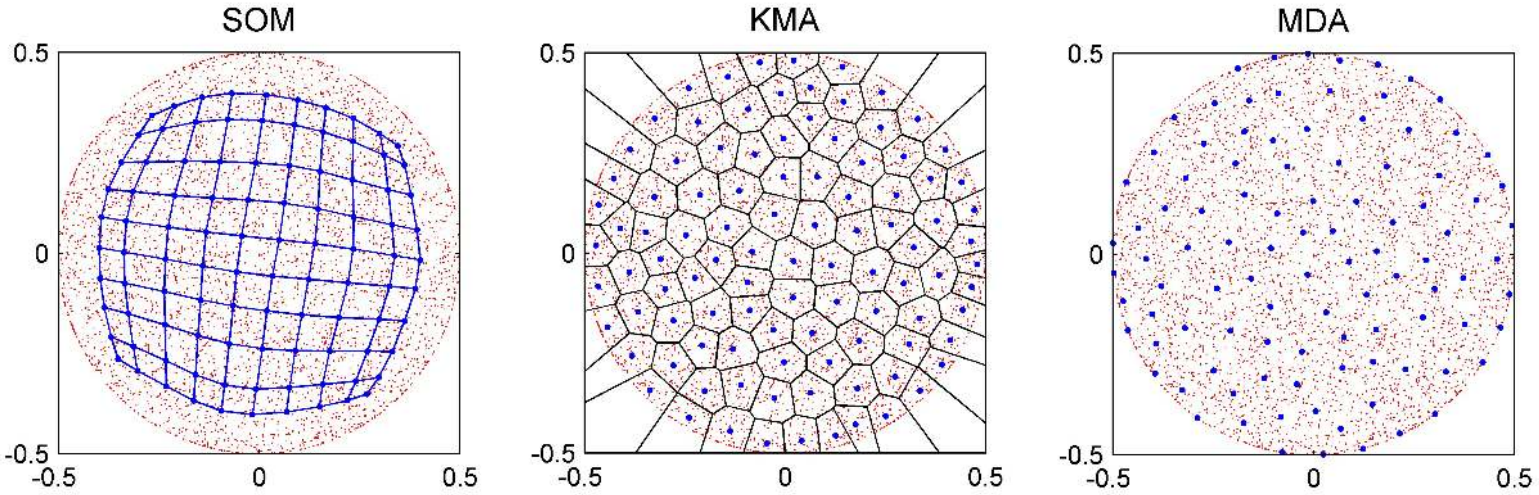
Wave variability along the coast



# Selection and classification techniques

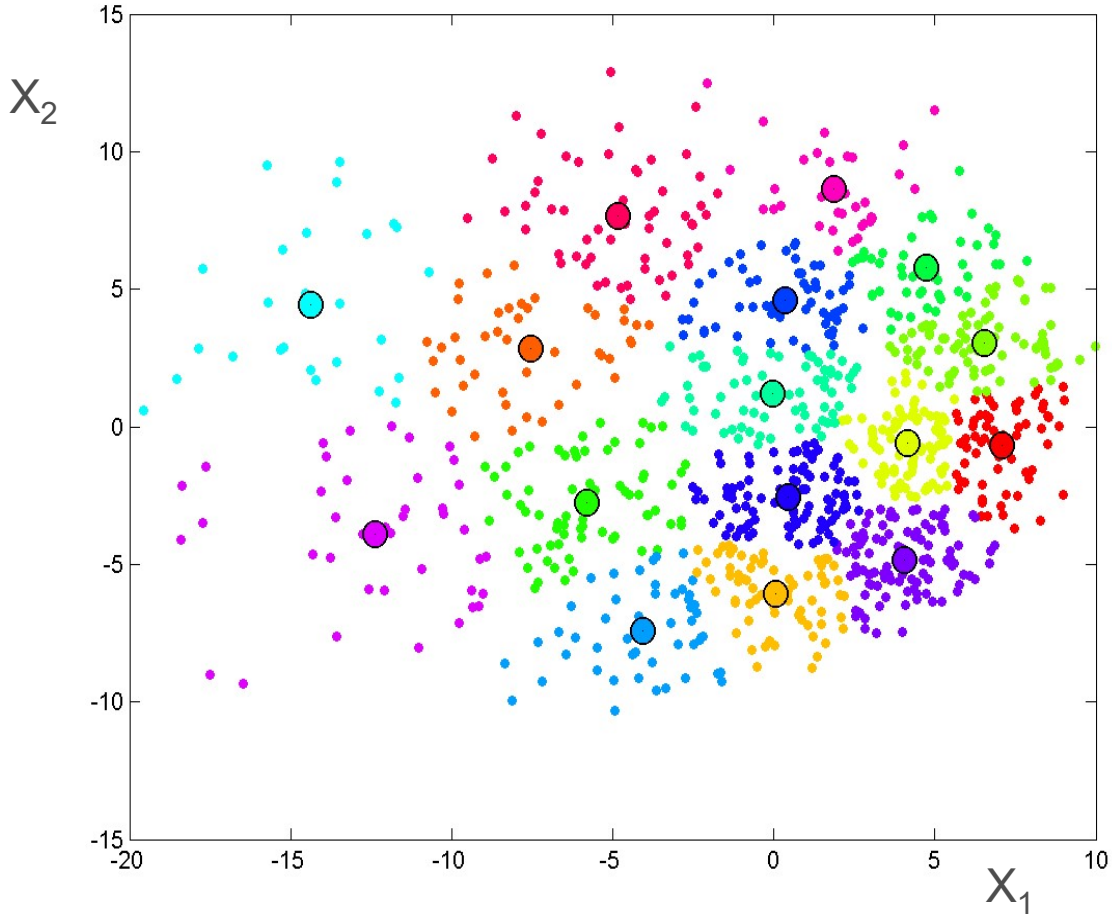
- Self-organizing maps (SOM)
- Kmeans algorithm (KMA)
- Maximum dissimilarity algorithm (MDA)



# Selection and classification techniques

$\{x_1, x_2, \ldots, x_N\}$ *N* data

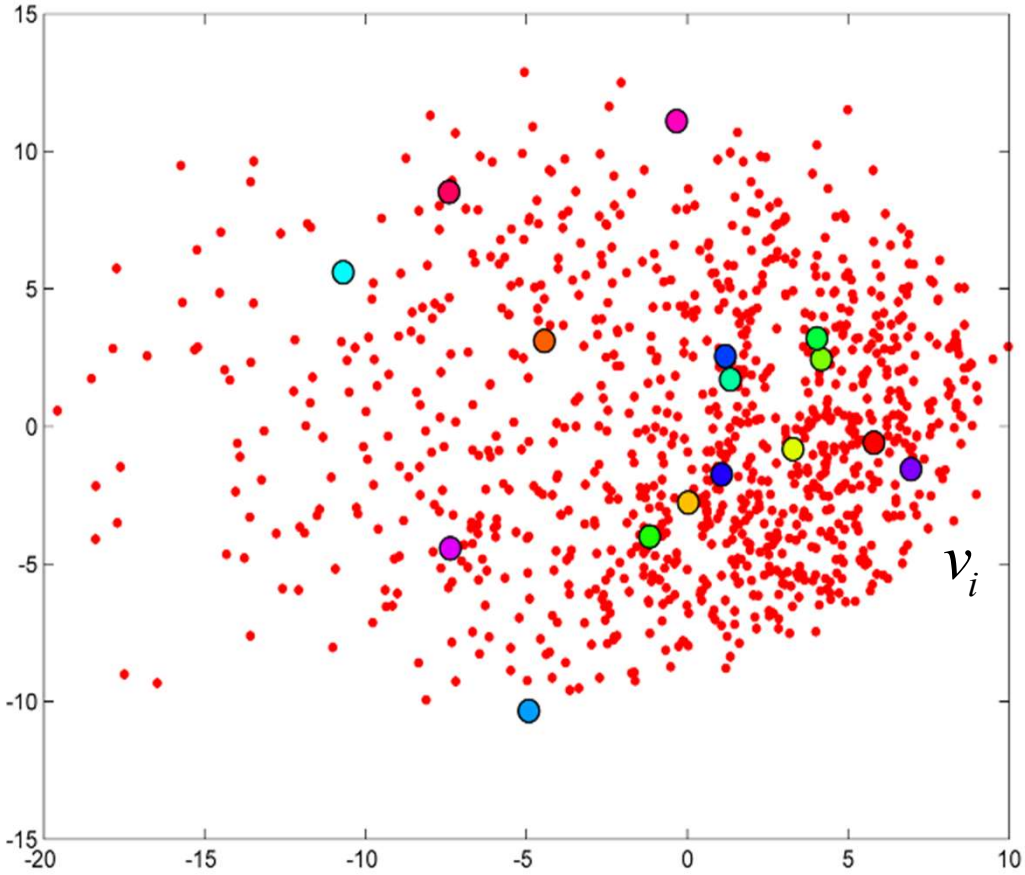
$\{v_1^0, \ldots, v_M^0\}$ *M* centroids or prototypes



# KMA

Bidimensional data sample

Goal: 16 groups – Random initialization $\left\{v_1^0, v_2^0, ..., v_M^0\right\}$

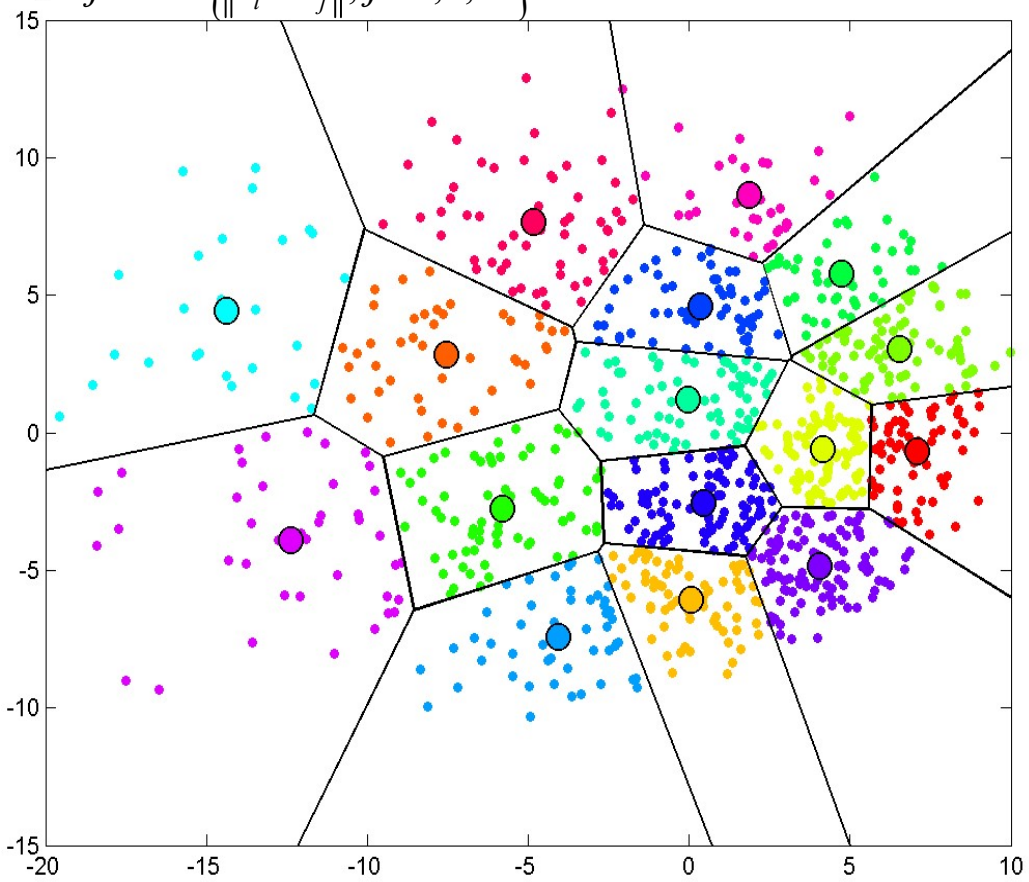


# KMA

Iteration *k*

$x_i$ → Belongs to the group *j* → The centroid *j* is updated as the mean of data belongs to that group

$$j = \min\left\{\left\|x_i - v_j\right\|, j = 1,..,M\right\}$$

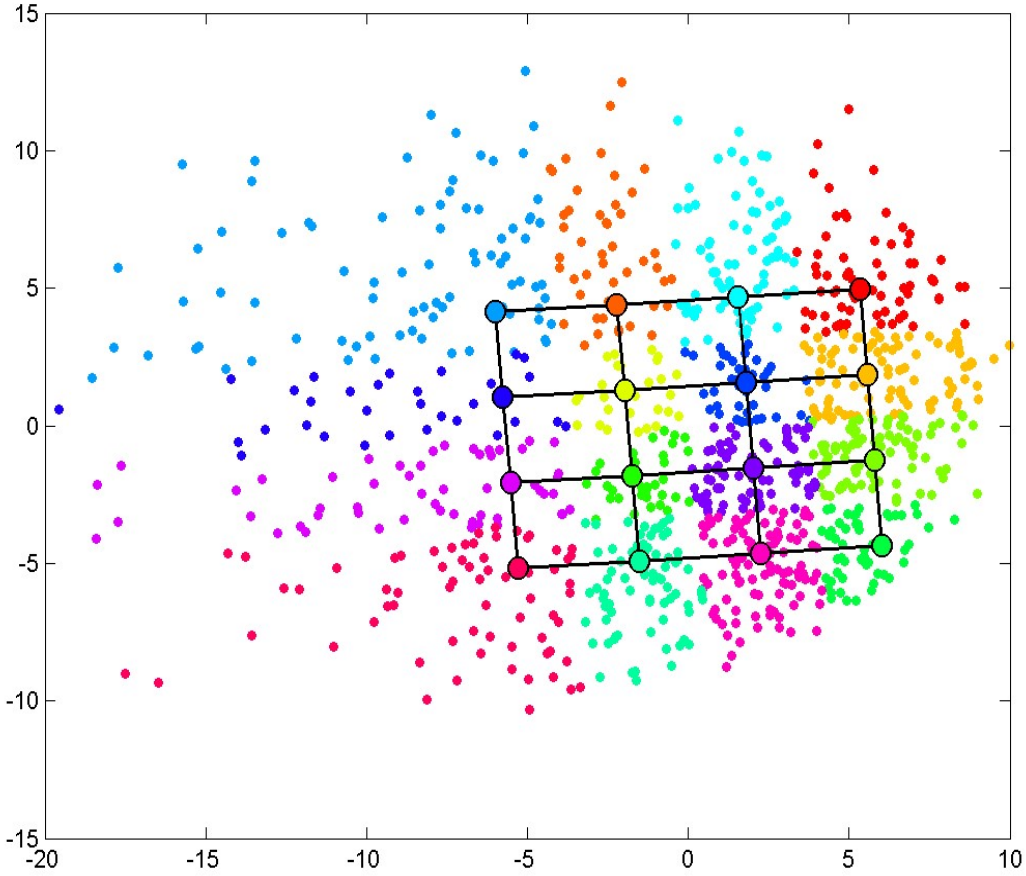



$$v_j^{r+1} = \sum_{x_i \in C_j} x_i / n_j$$

# SOM (self-organizing maps)

Bidimensional data sample

Goal: 16 groups –Initialization $\{v_1^0, v_2^0, ..., v_M^0\}$

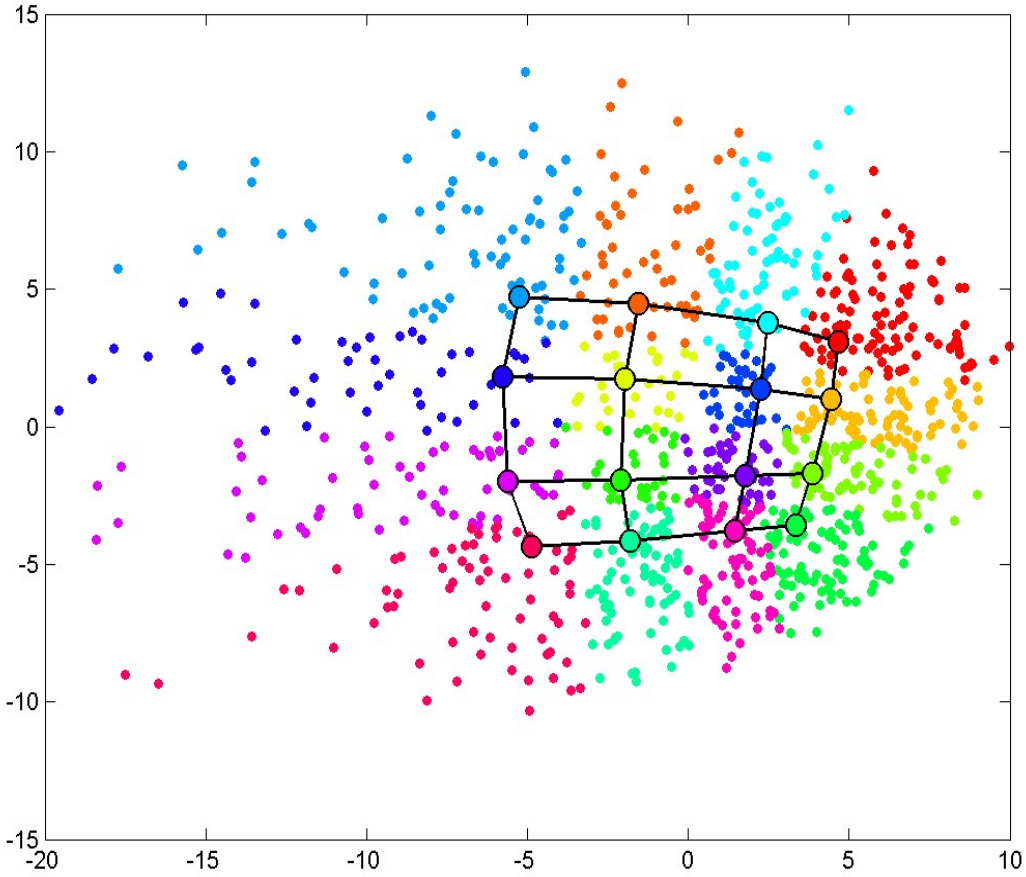


# SOM (self-organizing maps)

Training in cycles: $x_i \longrightarrow v_{w(i)} \longrightarrow$ Winning centroid

$$\left\| v_{w(i)} - x_i \right\| = \min_j \left\{ \left\| v_j - x_i \right\|, j = 1, \ldots, M \right\}$$

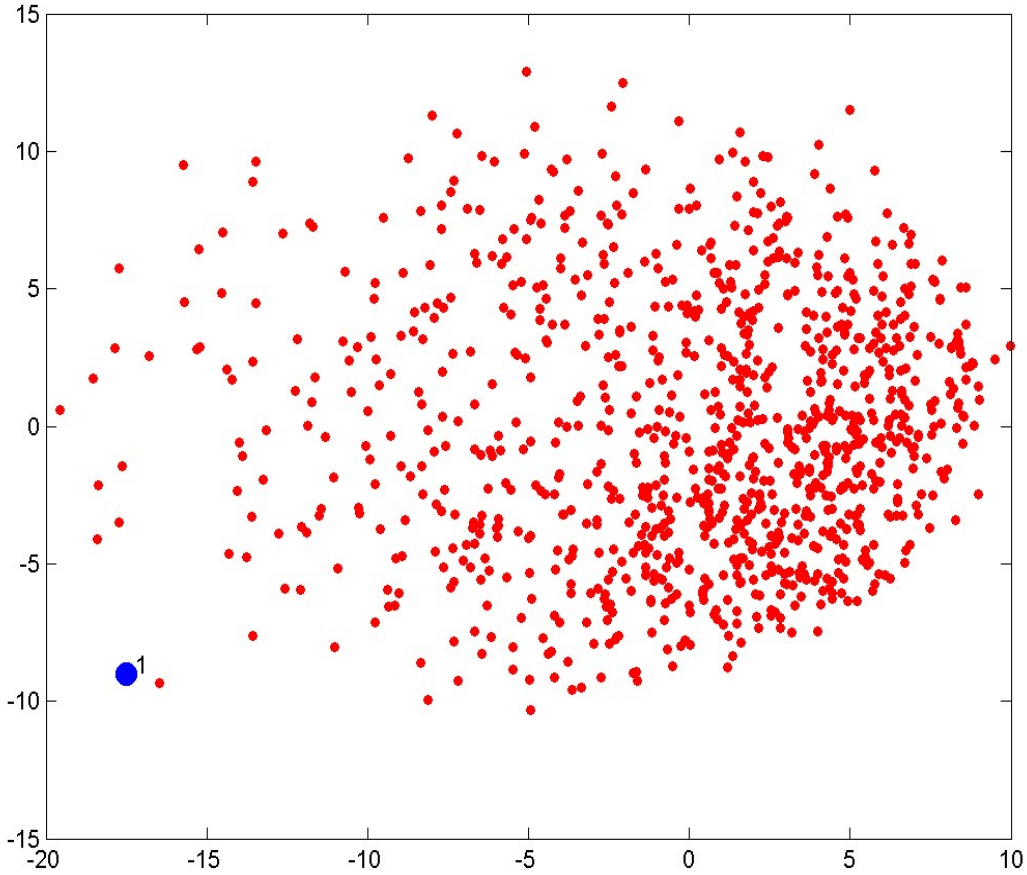
$$v_j = v_j + \alpha h(w(i), j)\left( x_i - v_j \right), j = 1, \ldots, M$$



# MDA (maximum dissimilarity algorithm)

Goal: subset of 16 elements

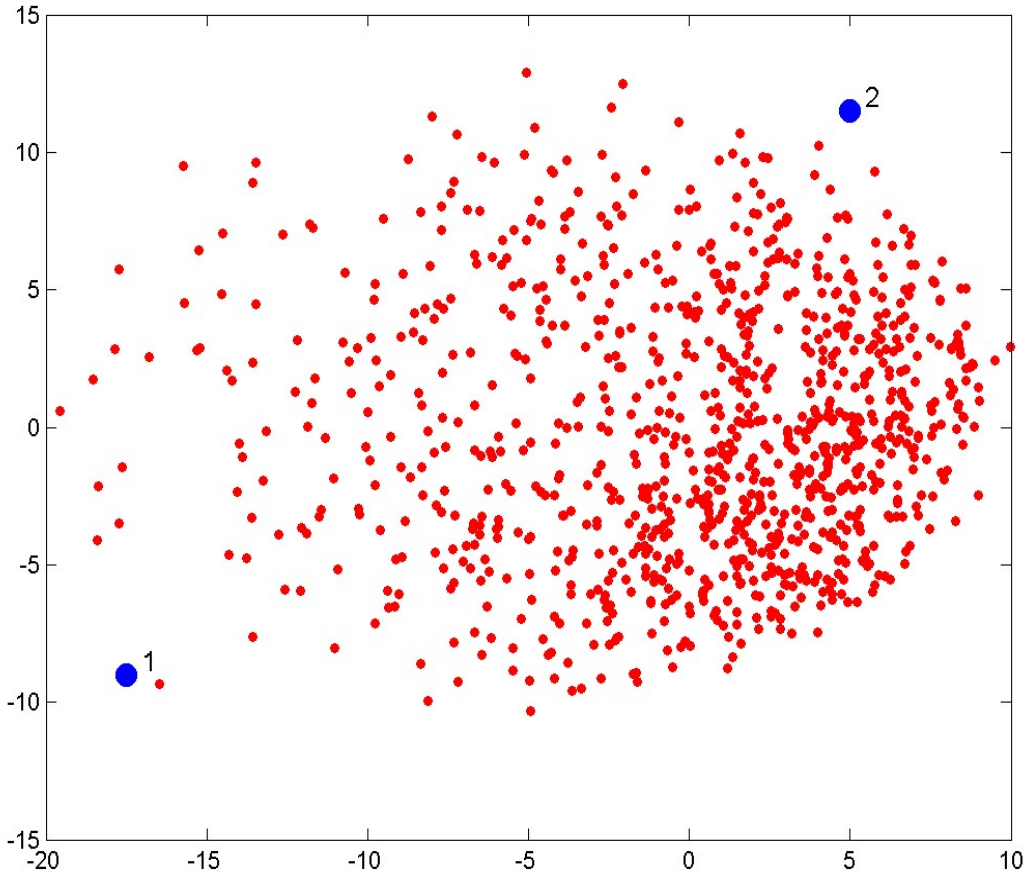
Initialization: the most different data $\longrightarrow D_i = \sum_{j=1}^{N-1} \left\| x_i - x_j \right\|; j = 1,\ldots,N \longrightarrow \max\{D_i; i = 1,\ldots,N\}$



# MDA (maximum dissimilarity algorithm)

Subset: $\{v_1\}$

New data of the subset: $\{v_2\}$ $\max\left\{d_{i,subconjunto} = \left\|x_i - v_1\right\|; i = 1,\ldots,N-1\right\}$



# MDA (maximum dissimilarity algorithm)

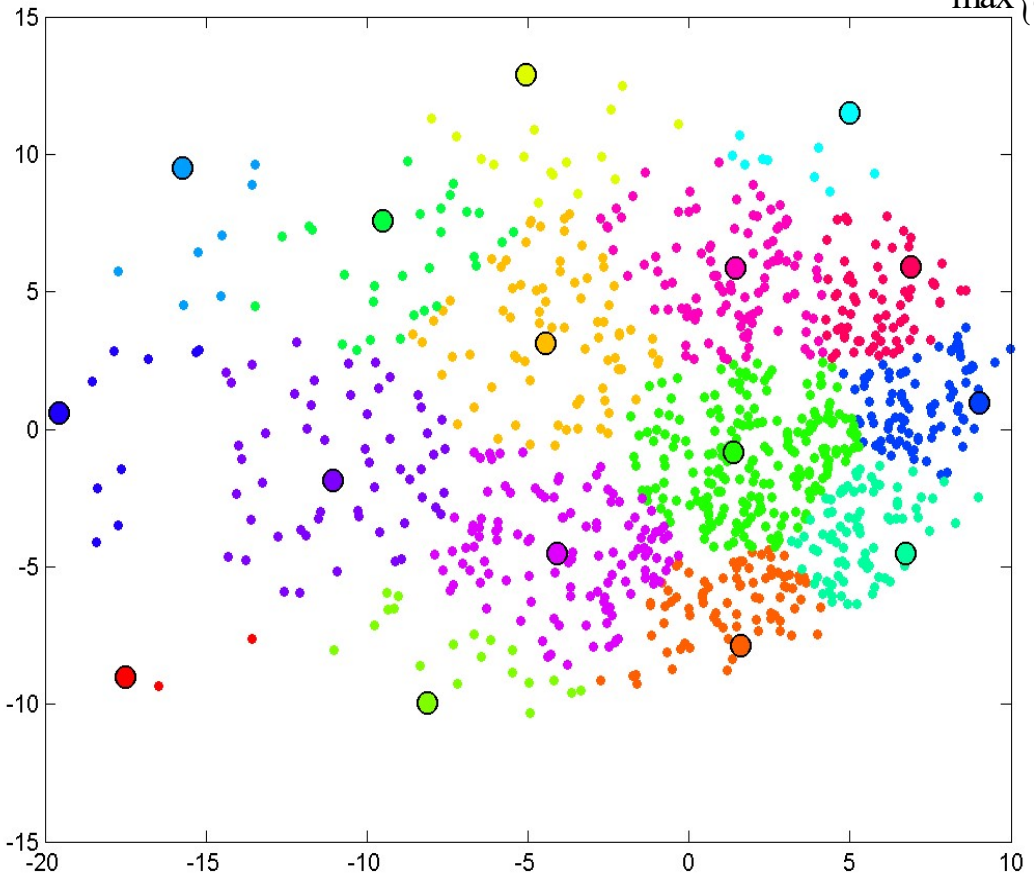
Subset: $\{v_1, v_2\}$

New data of the subset: $\{v_3\}$

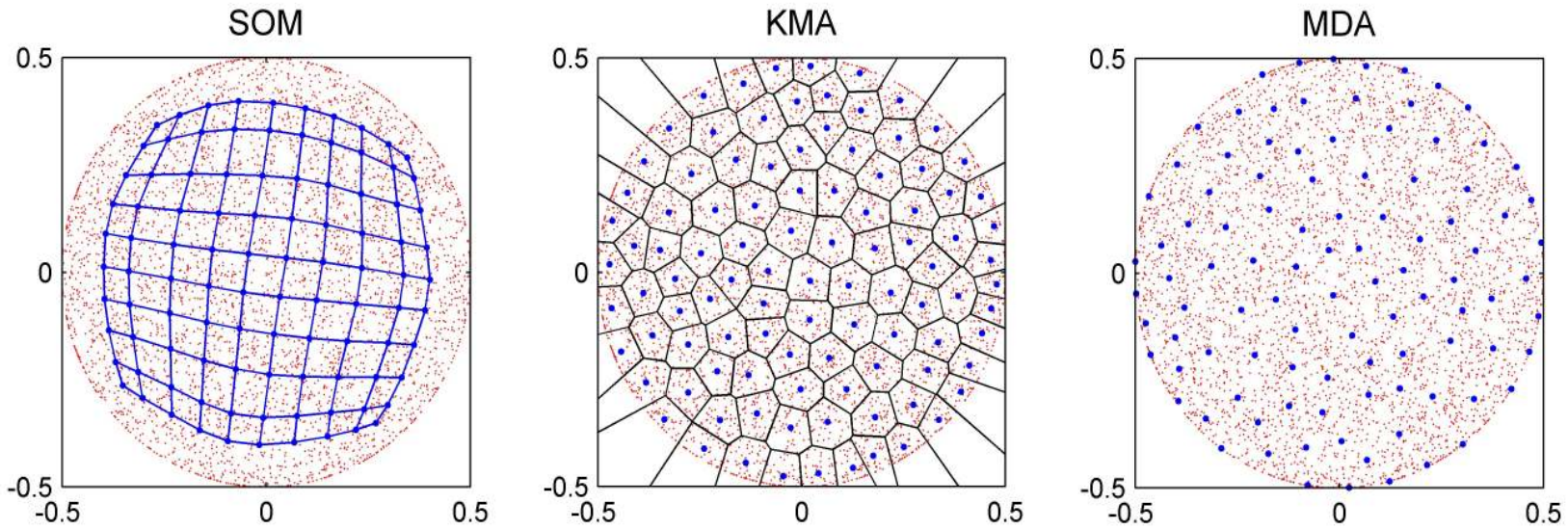
$$d_{ij} = \left\| x_i - v_j \right\|; i = 1,\ldots,N-2; j = 1,\ldots,2$$

$$d_{i,subconjunto} = \min\left\{ \left\| x_i - v_j \right\|; j = 1,\ldots,2 \right\}; i = 1,\ldots,N-2$$

$$\max\left\{ d_{i,subconjunto}; i = 1,\ldots,N-2 \right\}$$

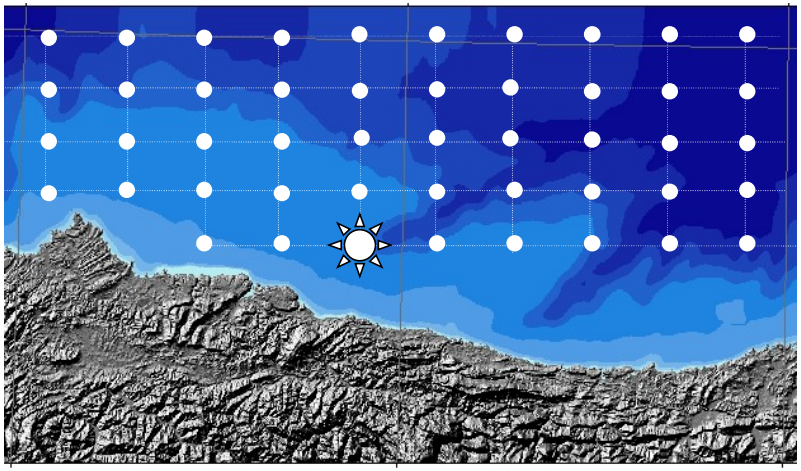


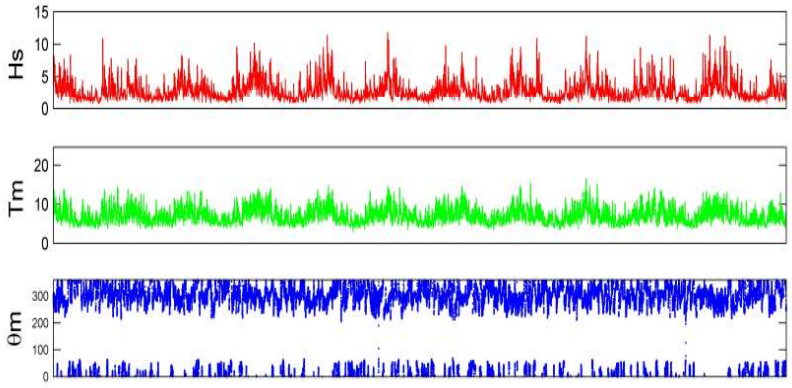
# Selection and classification techniques



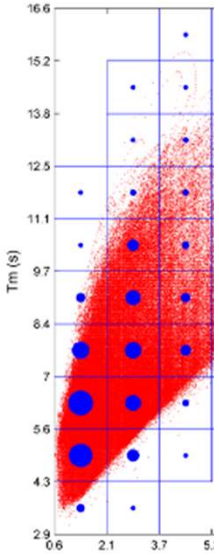

Camus, P., Méndez, F.J., Medina, R., Cofiño, A. (2011) Analysis of clustering and selection algorithms for the study of multivariate wave climate, Coastal Engineering, doi:10.1016/j.coastaleng.2011.02.003

# Multidimensional characterization of Wave Climate
# Hs, Tm, θm

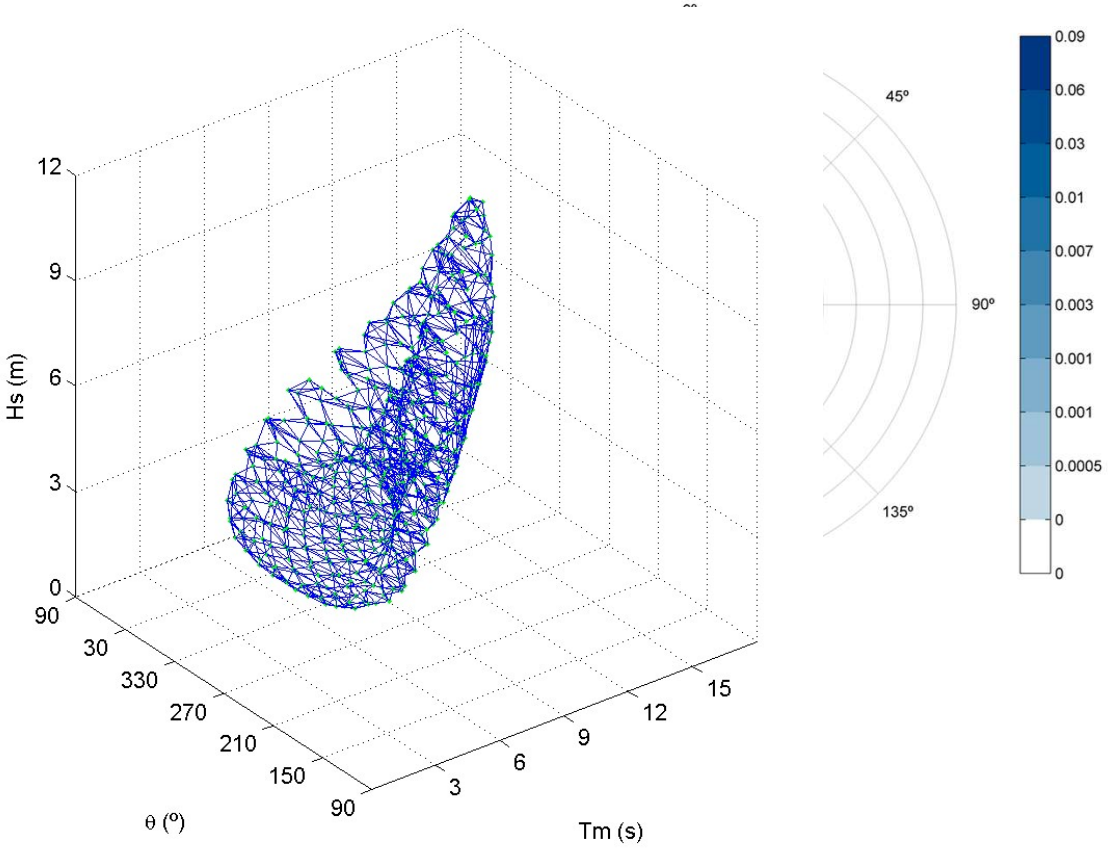





Probability ($H_s$, $T_m$)



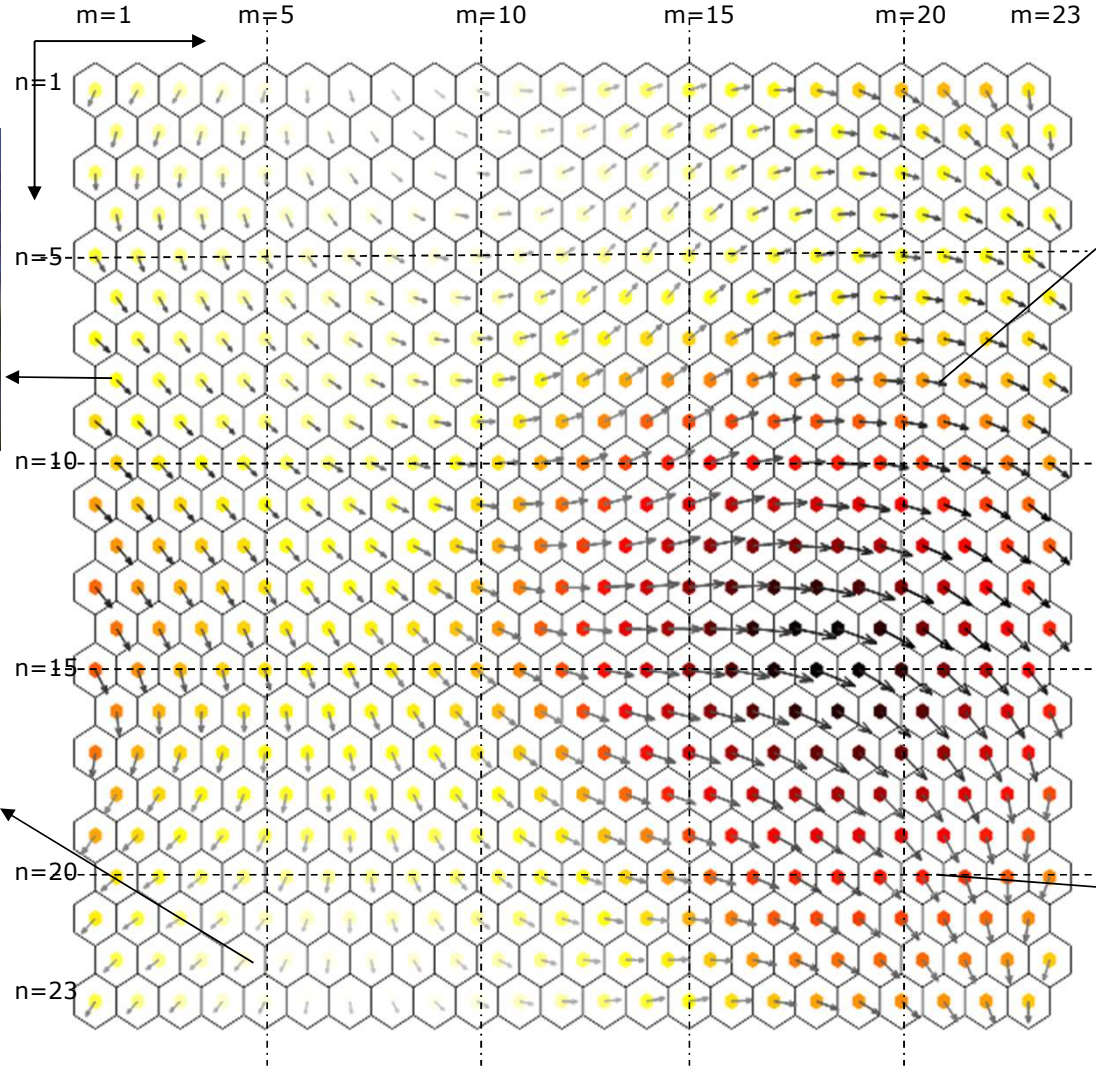

Probability ($H_s$, $\vartheta_m$)

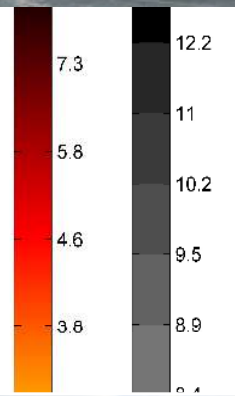


# Multidimensional characterization of Wave Climate

**SOM *M*=529 (23x23)**
**Wave climate: {$H_s$, $T_m$, $\theta_m$}**

"***Sea State types***" in one location

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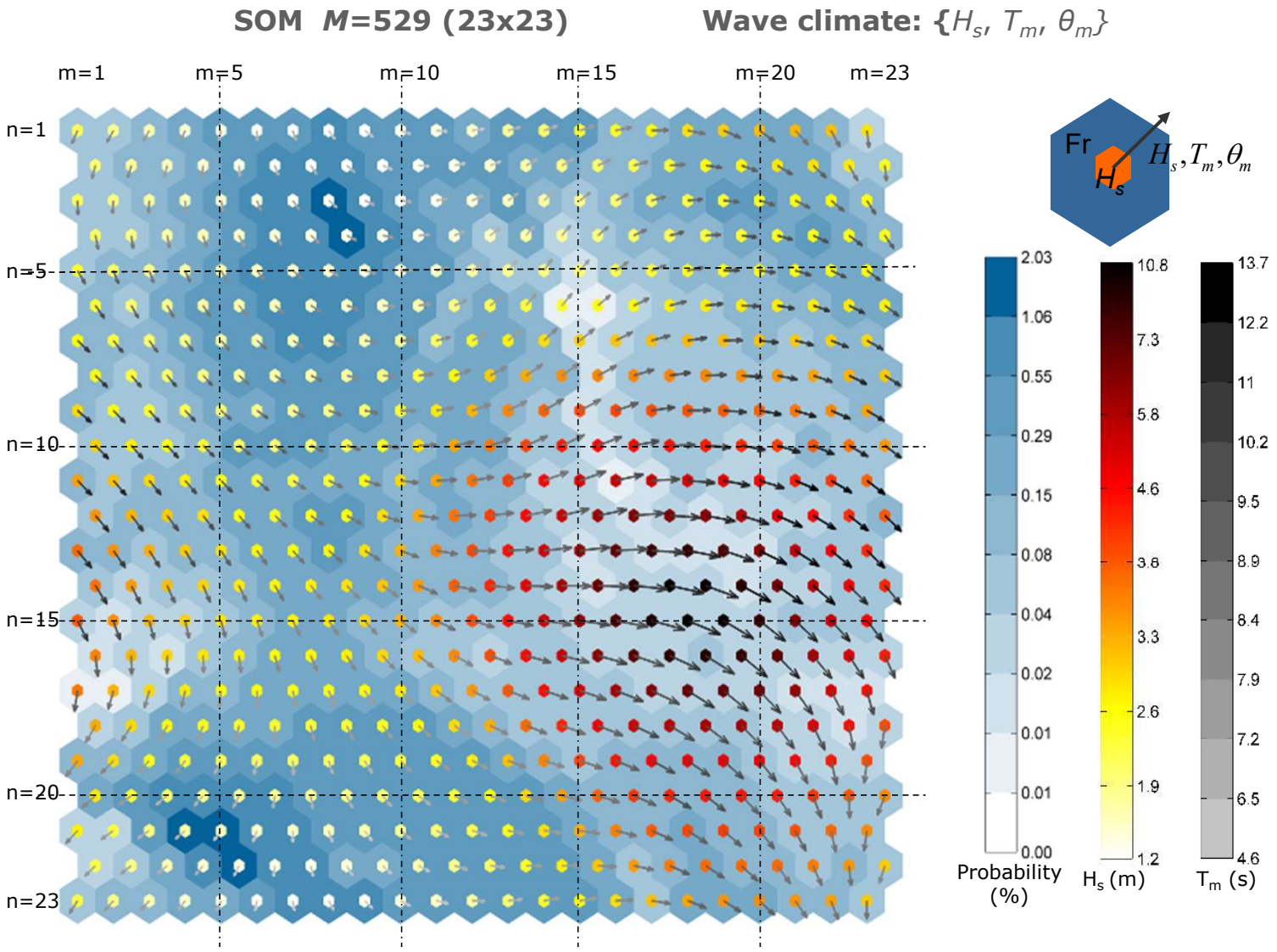
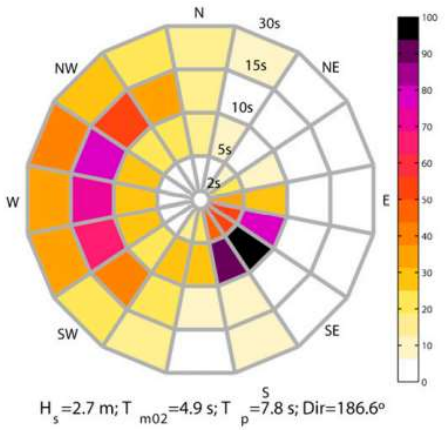
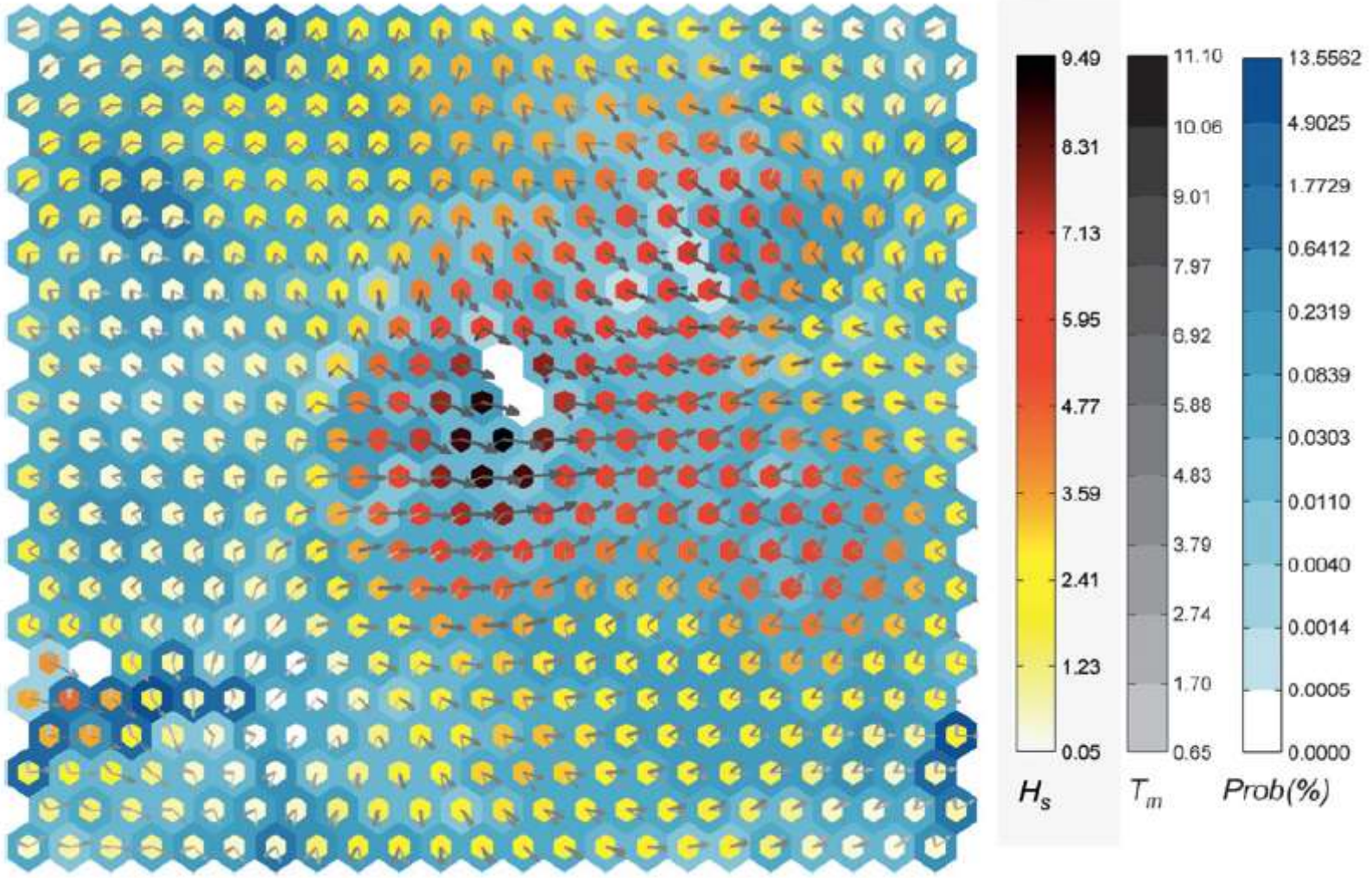
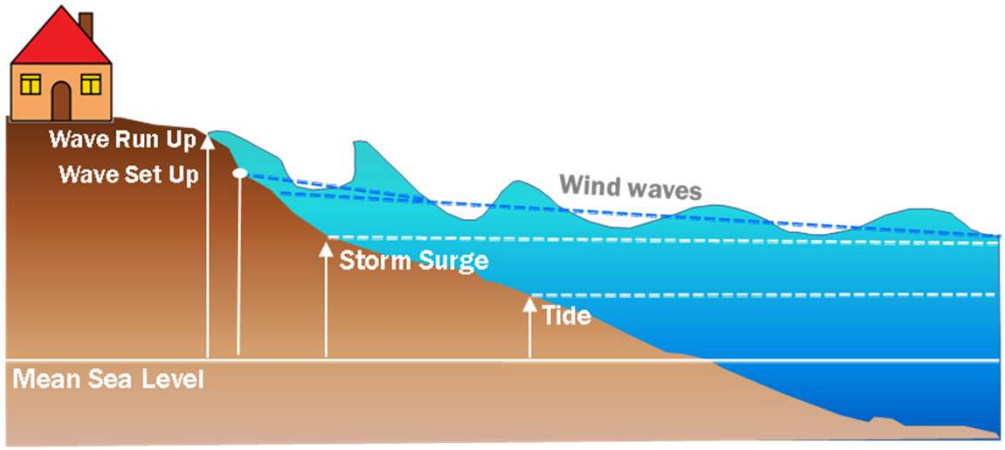


# Multidimensional characterization of Wave Climate
## Hs1, Tm1, θm1, Hs2, Tm2, θm2



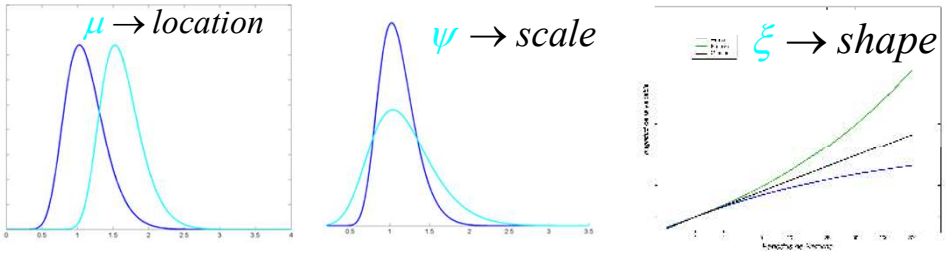



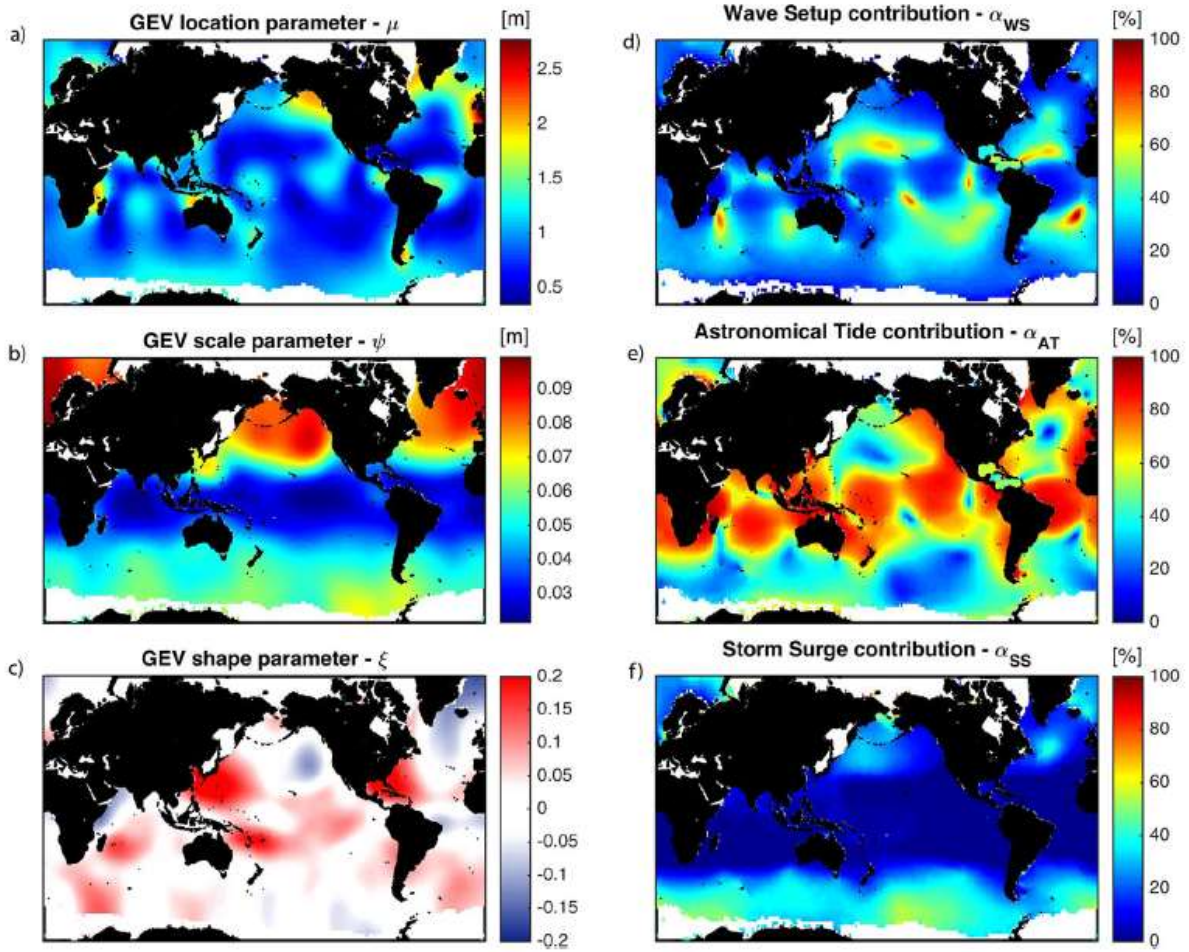
# A global classification of coastal flood hazard climates associated with large-scale oceanographic forcing




GENERALIZED EXTREME VALUE ANALYSIS

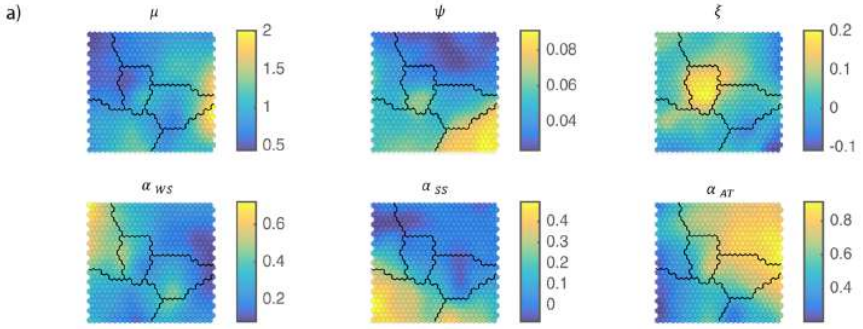
$$F(x;\theta) = \exp\left\{-\left[1+\xi\left(<\frac{x-\mu}{\psi}\right)\right]^{-1/\xi}\right\}$$

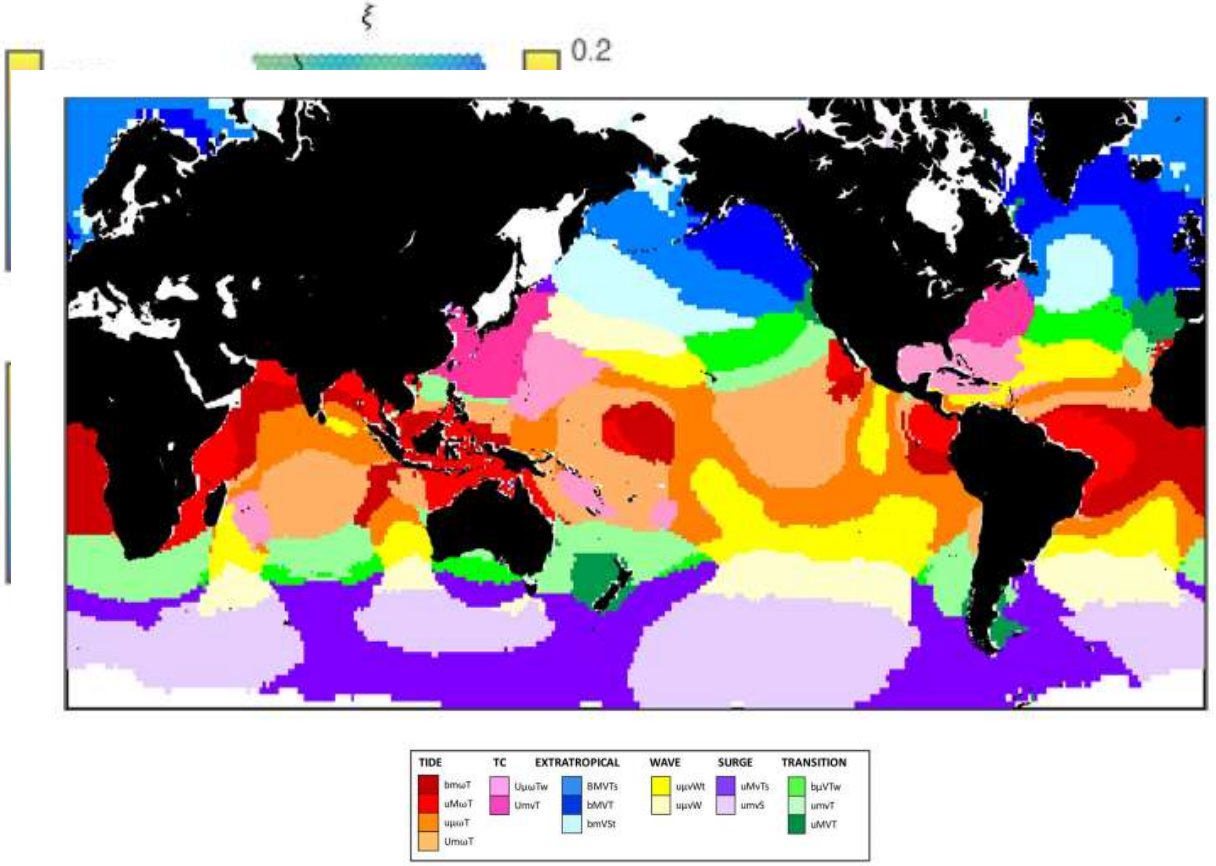



Rueda et al., 2017

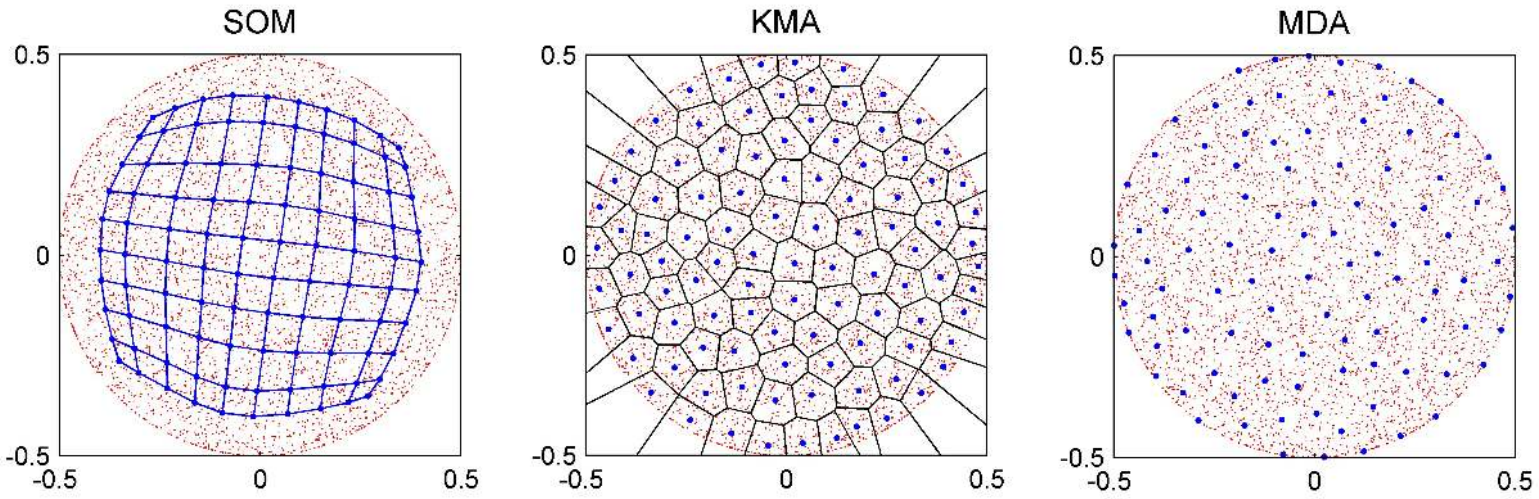
# A global classification of coastal flood hazard climates associated with large-scale oceanographic forcing



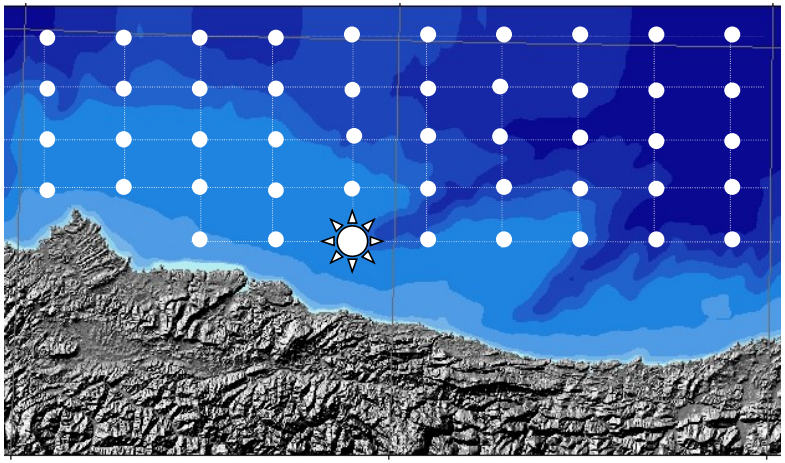

Rueda et al., 2017

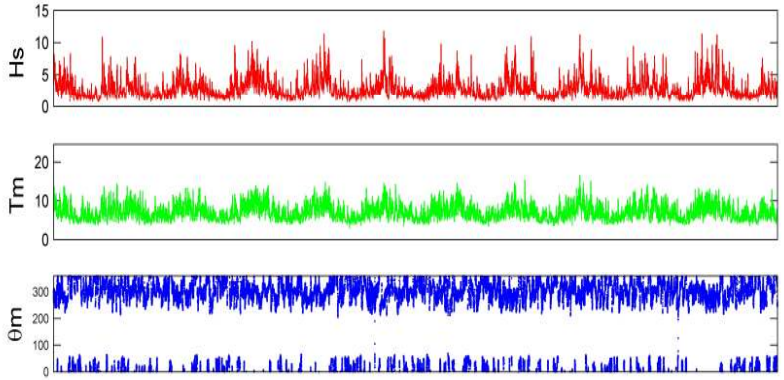
# Selection and classification techniques



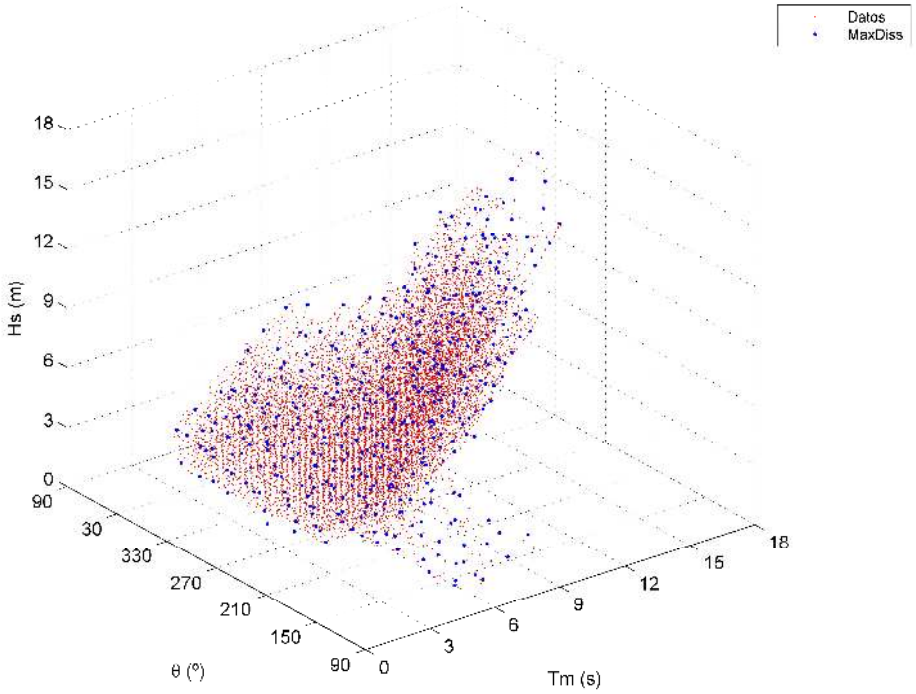

Camus, P., Méndez, F.J., Medina, R., Cofiño, A. (2011) Analysis of clustering and selection algorithms for the study of multivariate wave climate, Coastal Engineering, doi:10.1016/j.coastaleng.2011.02.003

# Multidimensional Wave Climate
## Hs, Tm, θm

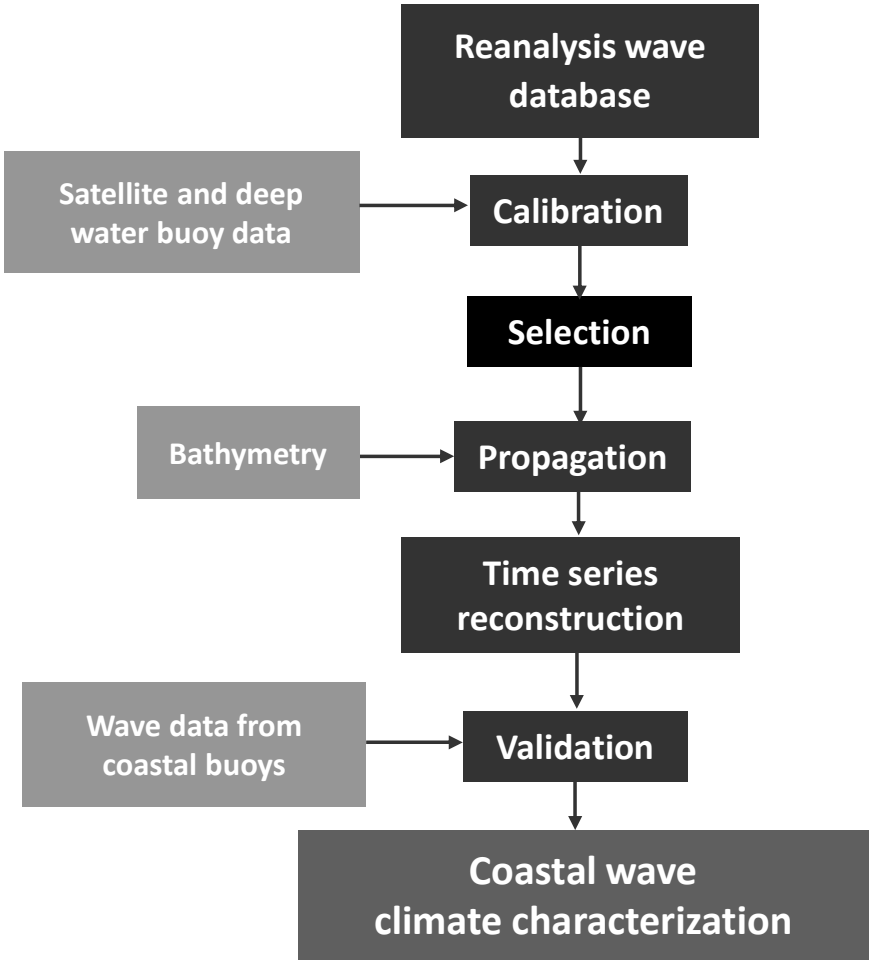


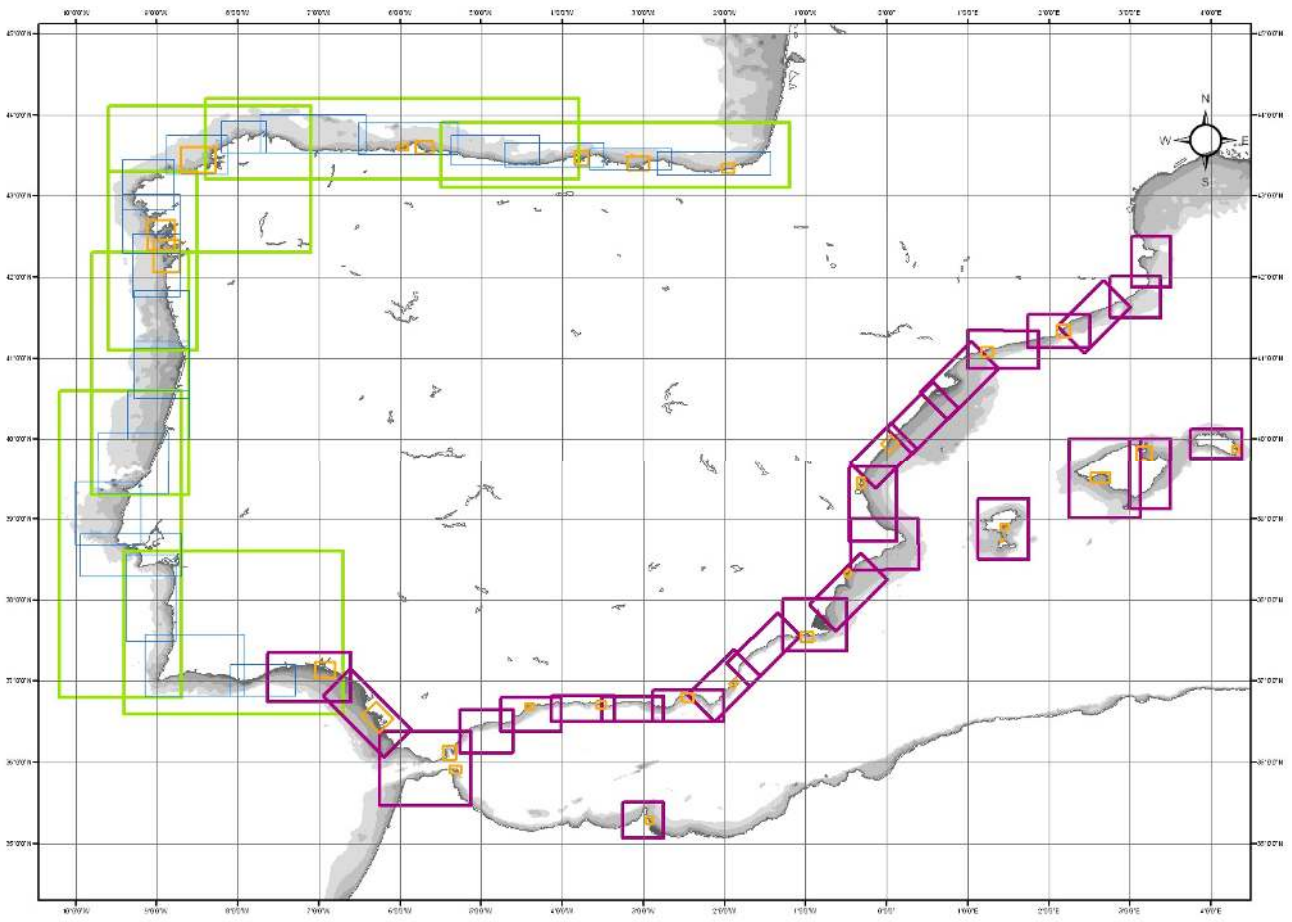



MDA



# Downscaled Ocean Waves (DOW) hindcast



Camus et al., 2013

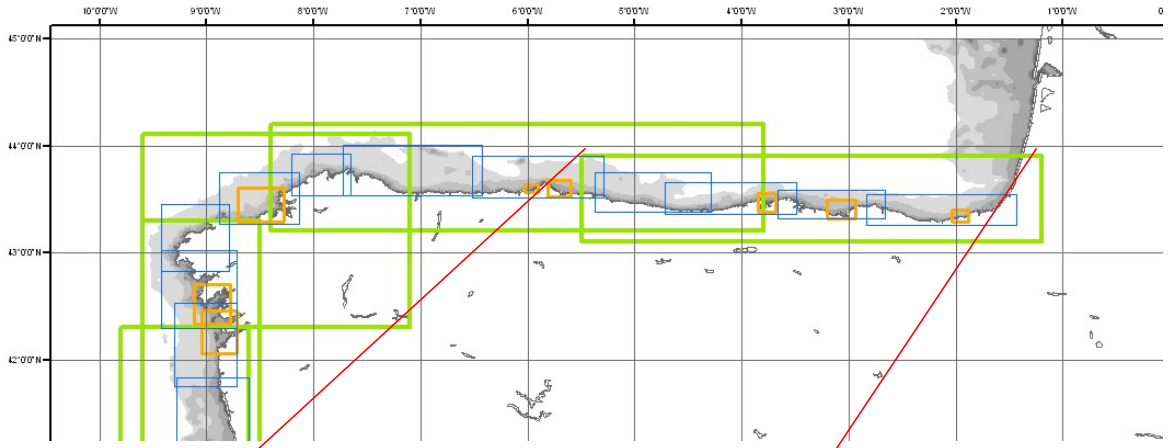
# Downscaled Ocean Waves (DOW) hindcast

Historical data bases

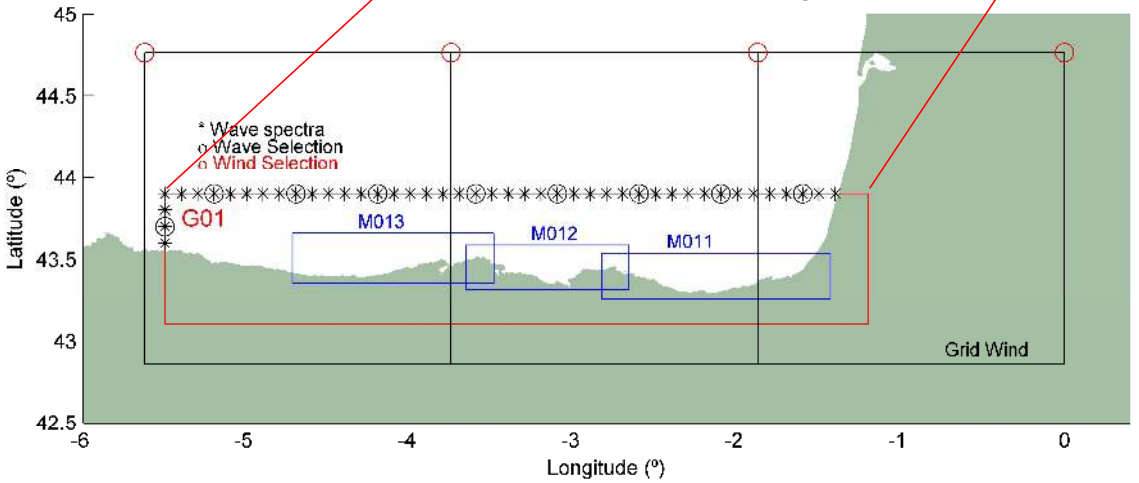
Selection

Propagation

Reconstruction



**Waves: GOW 1.0 – 1948-2008**
**Wind: NCEP**



# Downscaled Ocean Waves (DOW) hindcast

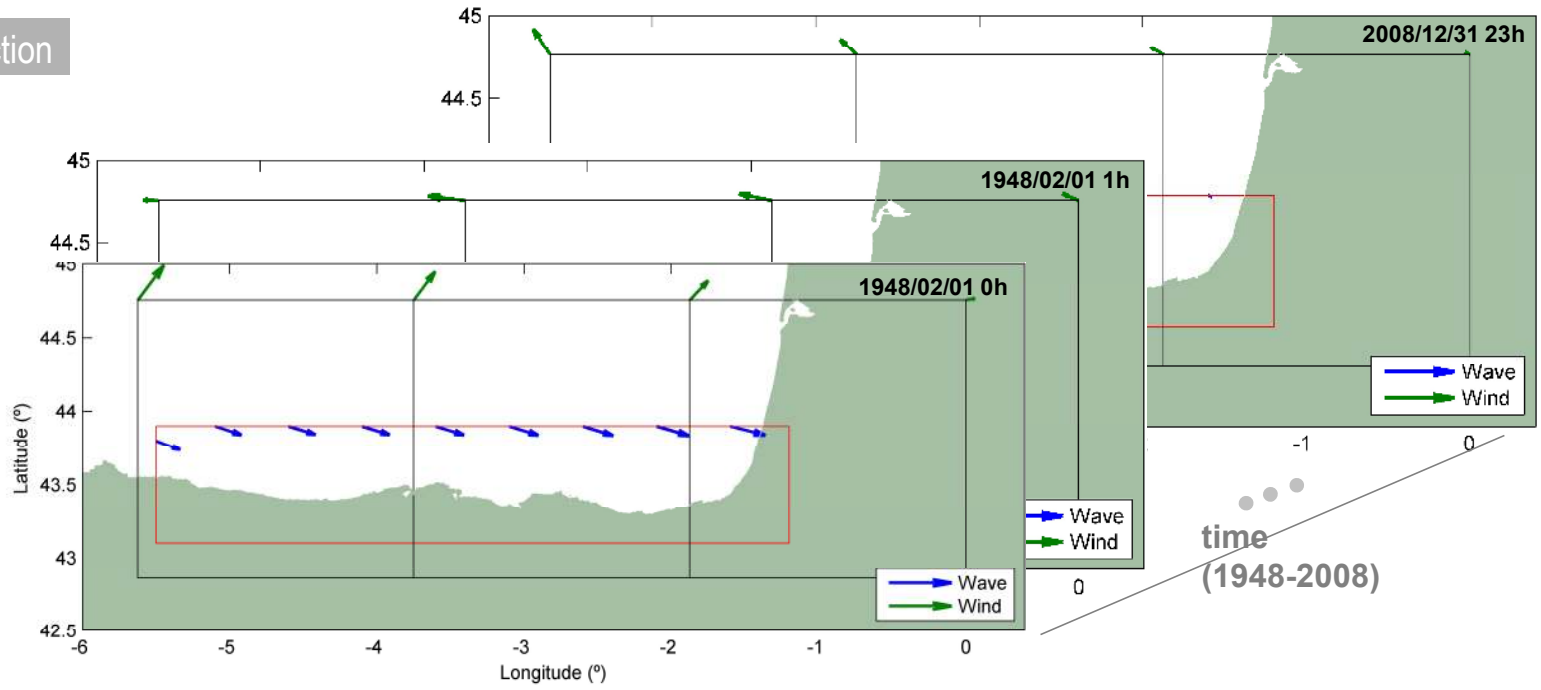
Historical data bases

Selection

Propagation

Reconstruction

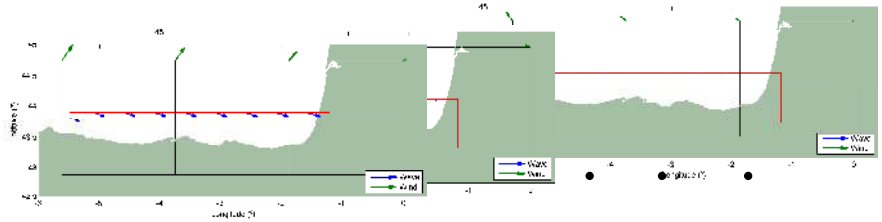
Time series of boundary conditions



# Downscaled Ocean Waves (DOW) hindcast

a) CALIBRATED DATA:

$$X_i^* = \left\{H_{s,1}, T_{m,1}, \theta_{m,1}, ..., H_{s,n1}, T_{m,n1}, \theta_{m,n1}, W_{10x,1}, W_{10y,1}, ..., W_{10x,n2}, W_{10y,n2}\right\}_i \qquad i = 1, ..., N$$



**Standarization (the wave direction has been transformated to *x* and *y* components):**

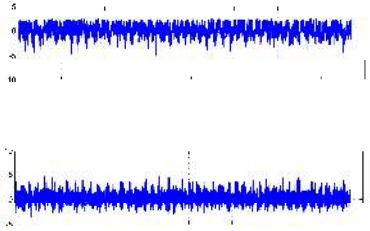
$$X_i = \left\{H_1, T_1, \theta_{x,1}, \theta_{y,1}, ..., H_{n1}, T_{n1}, \theta_{x,n1}, \theta_{y,n1,}, W_{x,1}, W_{y,1}, ..., W_{x,n2}, W_{y,n2}\right\}_i \qquad i = 1, ..., N$$

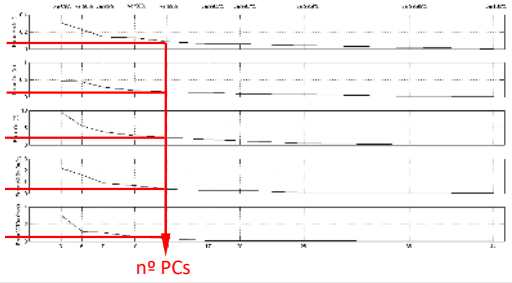
b) PCA to the calibrated data:

$EOF_{X1}(x)$ x $PC_{X1}(t_i)$

• • •

$EOF_{Xd}(x)$ x $PC_{Xd}(t_i)$

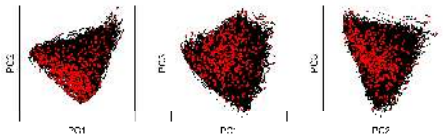


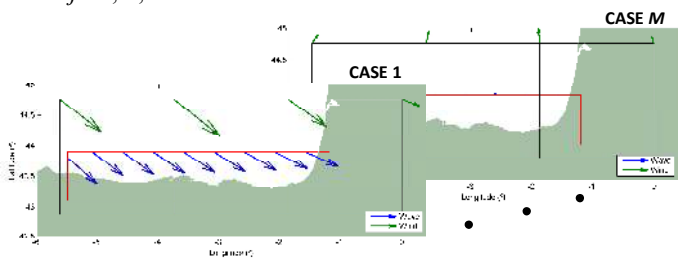



c) MDA:

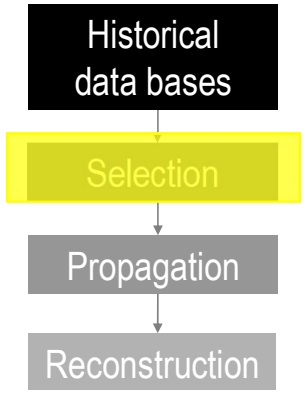
$$D_j^{EOF} = \left\{PC_{X1}, ..., PC_{Xd}\right\}_j \longrightarrow D_j = \left\{H_{s,1}^D, T_{m,1}^D, \theta_{m,1}^D, ..., H_{s,n1}^D, T_{m,n1}^D, \theta_{m,n1}^D, W_{10x,1}^D, W_{10y,1}^D, ..., W_{10x,n2}^D, W_{10y,n2}^D\right\}_j$$

$$j = 1, ..., M$$



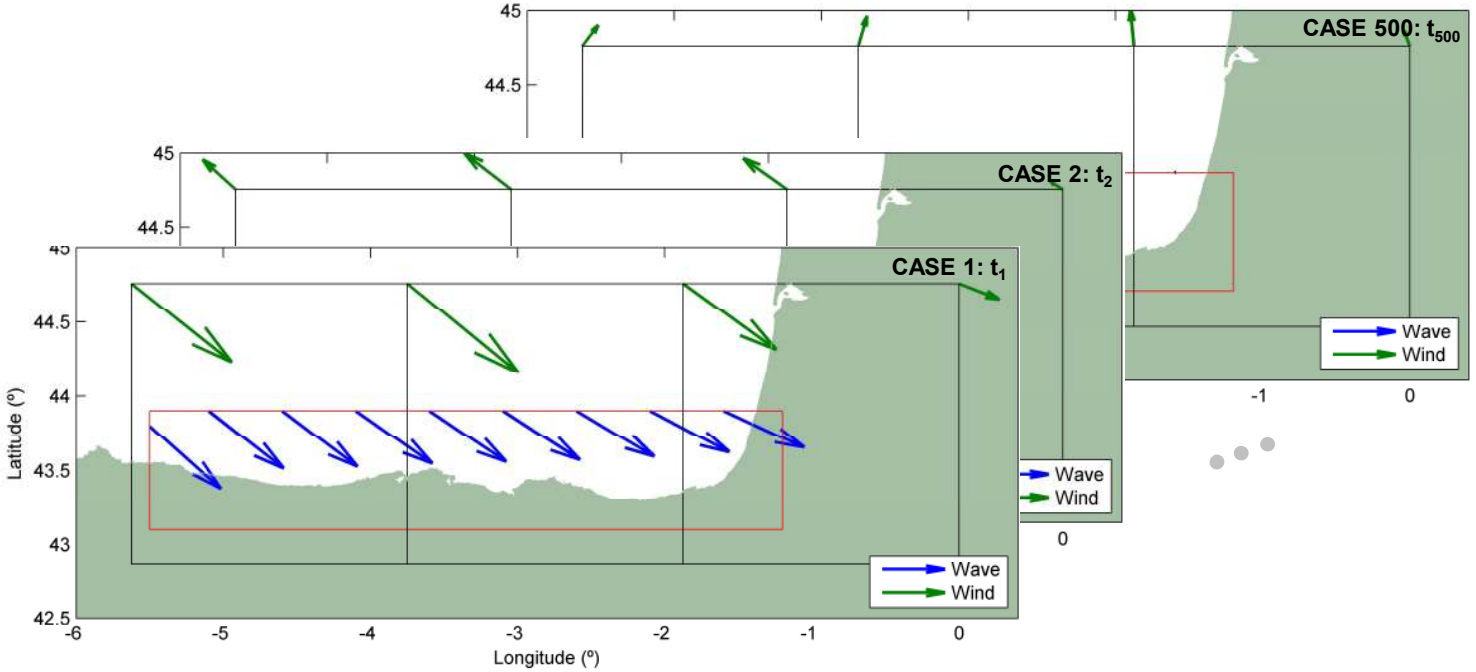


# Downscaled Ocean Waves (DOW) hindcast

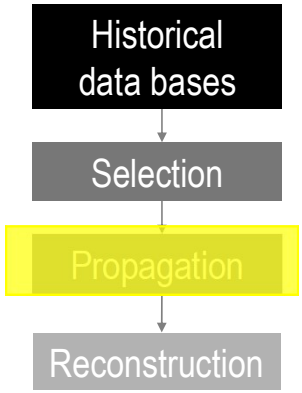



**MDA**

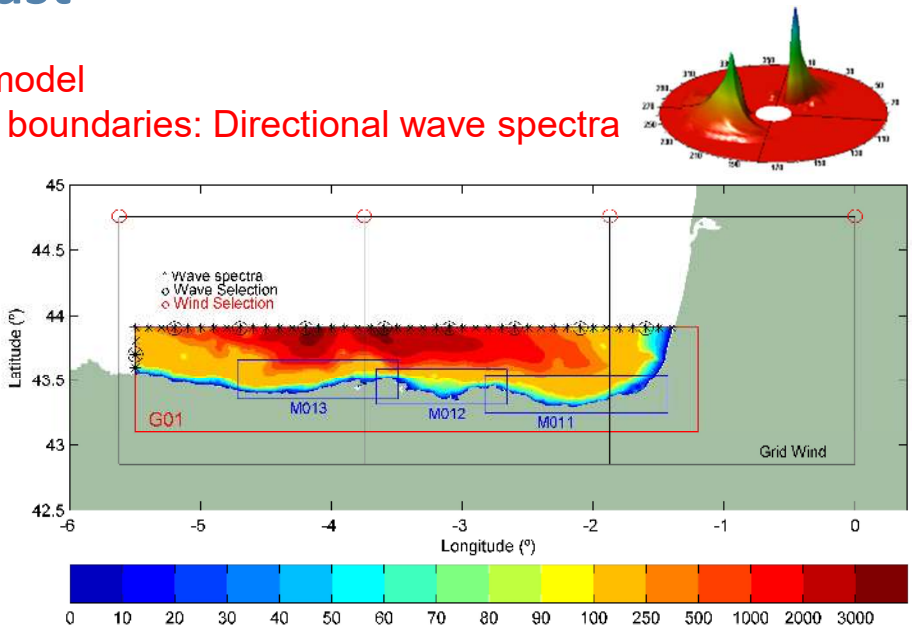
Selected cases (*M*=500)



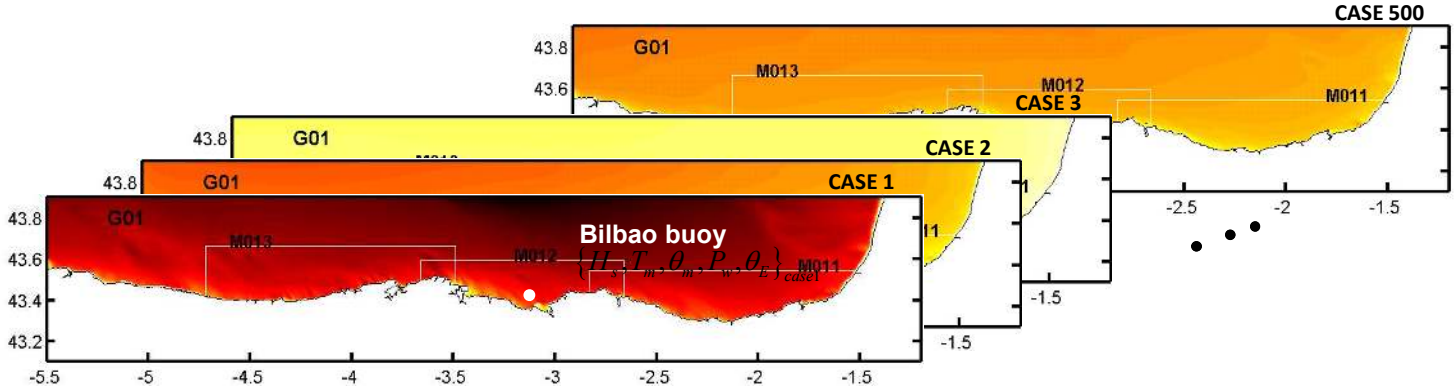
# Downscaled Ocean Waves (DOW) hindcast




SWAN model
Variable boundaries: Directional wave spectra




Catalog of *M*=500 propagated cases



# Downscaled Ocean Waves (DOW) hindcast

Historical data bases

Selection

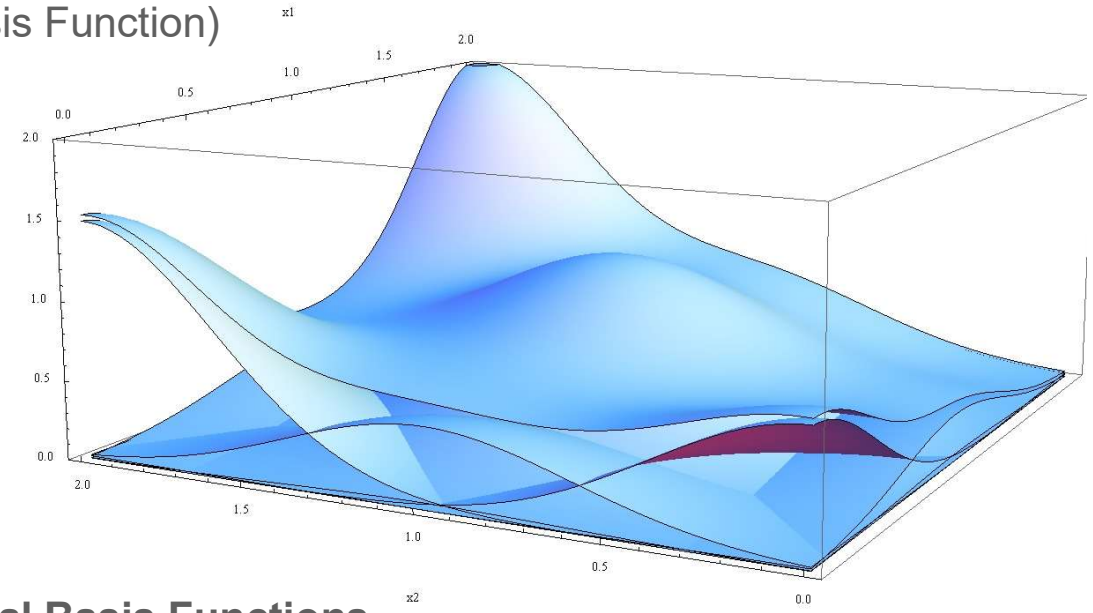
Propagation

Reconstruction

**RBF INTERPOLATION TECHNIQUE**

(Radial Basis Function)

Rippa 1999




**Radial Basis Functions**

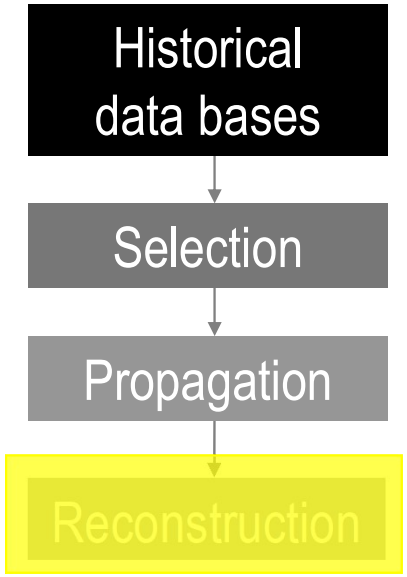
$$RBF\left(X_i\right) = p\left(X_i\right) + \sum_{j=1}^{M} a_j \Phi\left(\left\| X_i - D_j \right\|\right)$$

$$p\left(X_i\right) = b_0 + b_1 H_i + b_2 T_i + b_3 \theta_i + b_4 W_i + b_5 \beta_i$$

$$\Phi\left(\left\| X_i - D_j \right\|\right) = \exp\left(-\frac{\left\| X_i - D_j \right\|^2}{2c^2}\right)$$

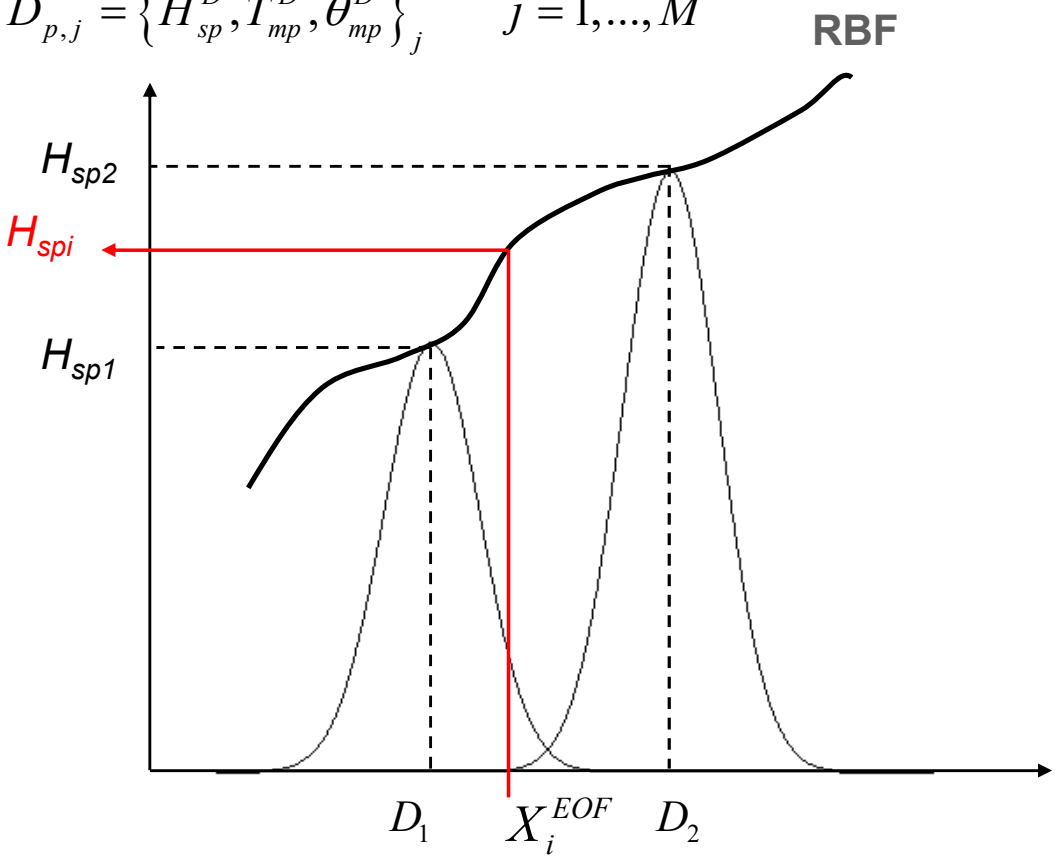
Camus et al., 2011

# Downscaled Ocean Waves (DOW) hindcast

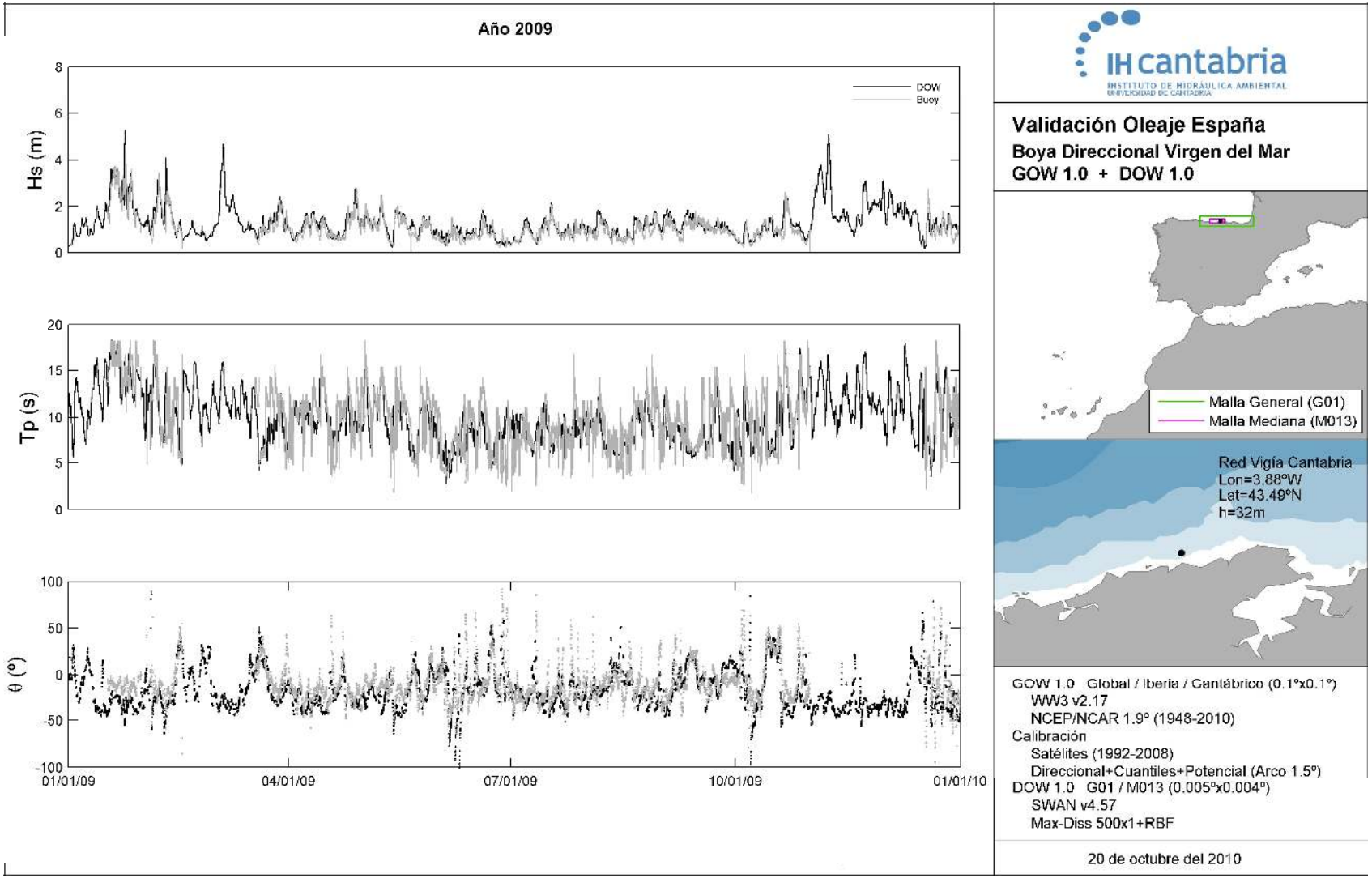



Propagated sea states parameters corresponding to *M* selected cases

$$D^{*}_{p,j} = \left\{ H^{D}_{sp}, T^{D}_{mp}, \theta^{D}_{mp} \right\}_{j} \qquad j = 1, \ldots, M$$

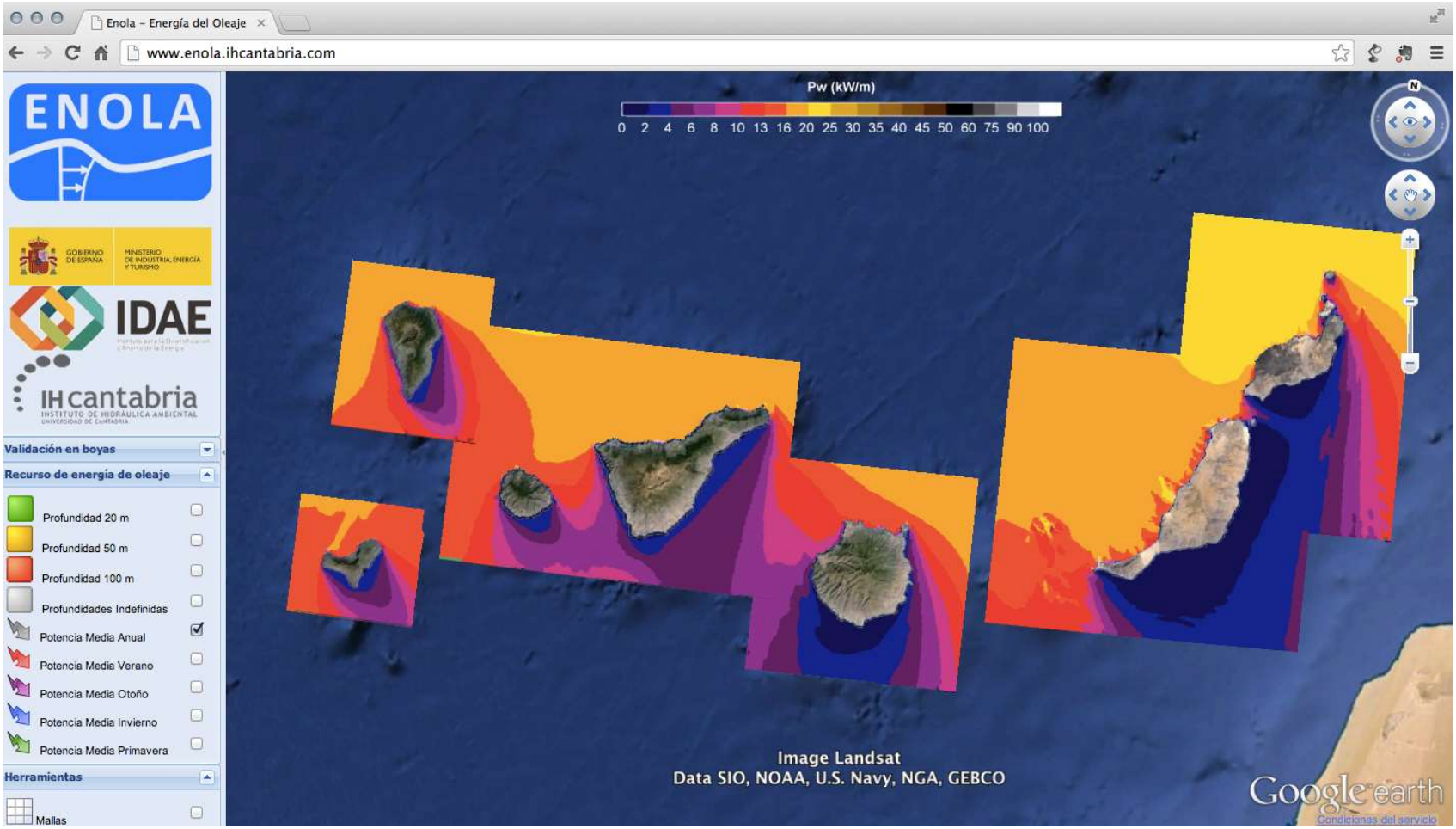


# Downscaled Ocean Waves (DOW) hindcast
# VALIDATION using instrumental data

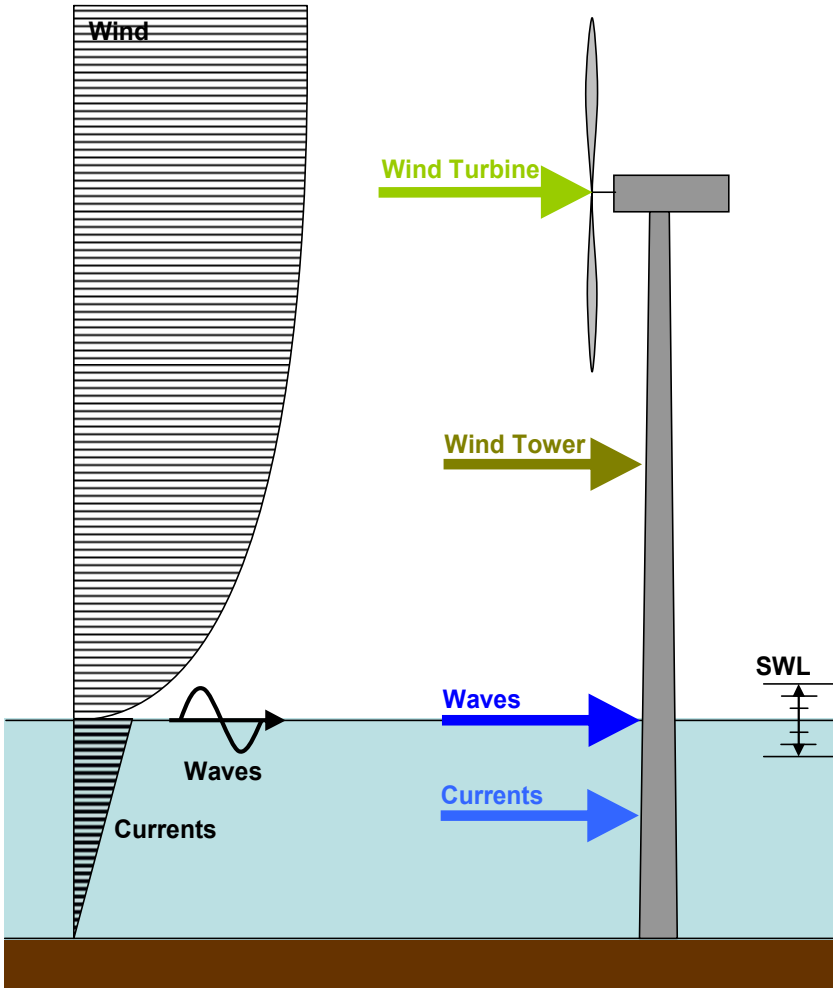


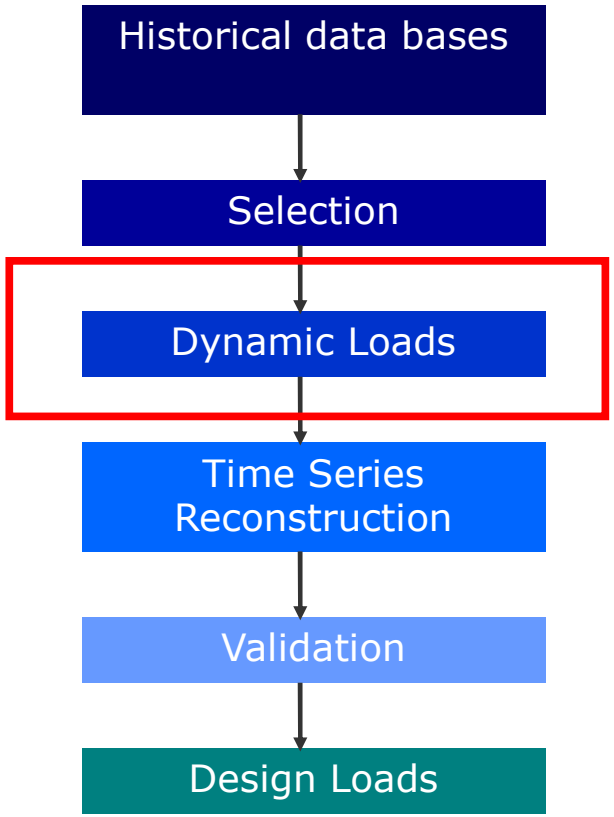
# Downscaled Ocean Waves (DOW) hindcast
# ATLAS of Wave Energy Resources

Annual mean wave energy (kW/m)



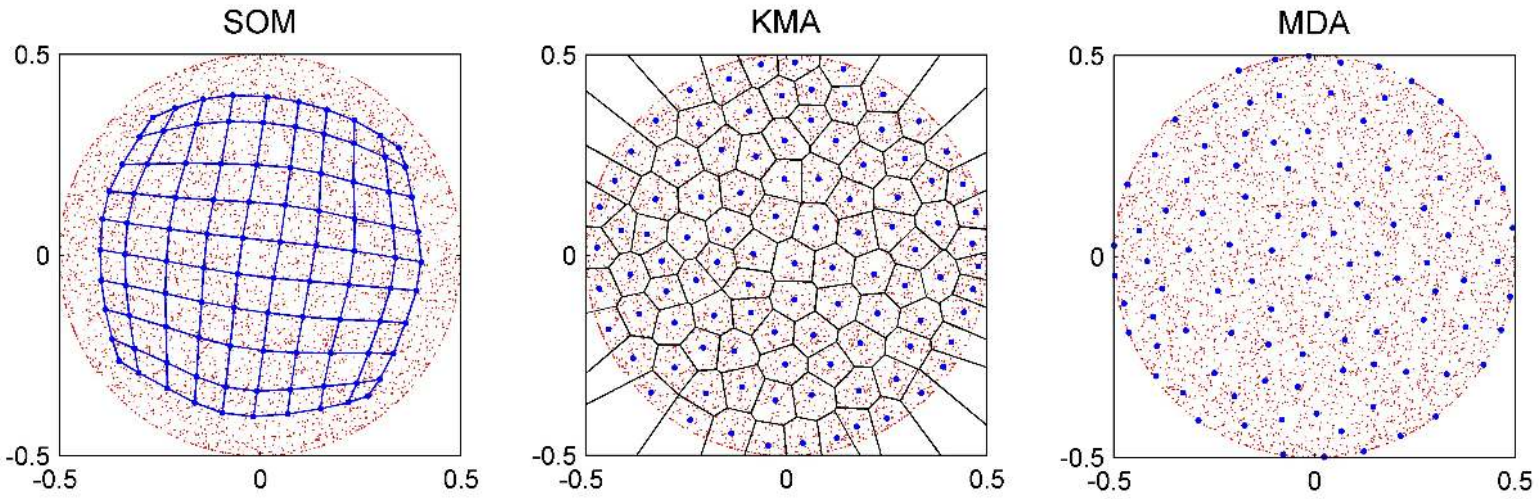
# Applications to determine loads for marine infrastructure design



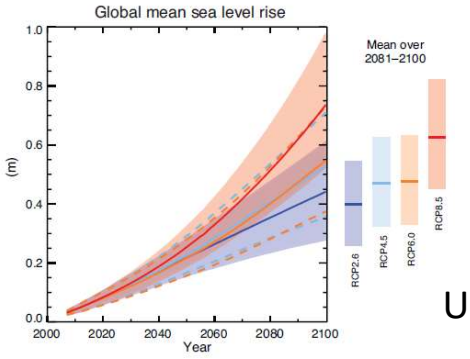

Guanche et al., 2011

# Selection and classification techniques

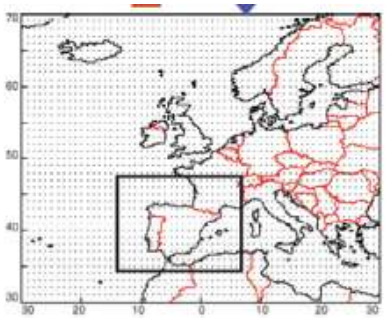



Camus, P., Méndez, F.J., Medina, R., Cofiño, A. (2011) Analysis of clustering and selection algorithms for the study of multivariate wave climate, Coastal Engineering, doi:10.1016/j.coastaleng.2011.02.003

# Statistical downscaling method to obtain climate change projections of waves



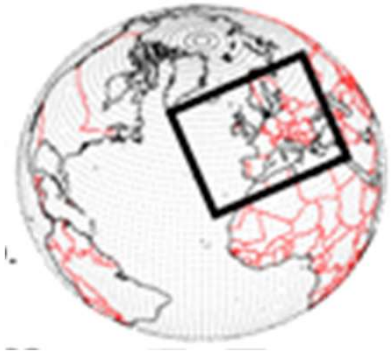

Uncertainty



RCP Scenarios

Uncertainty

Ensemble Global Circulation Models

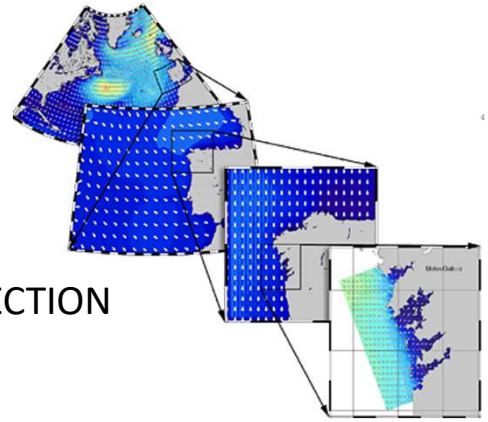


Ensemble Regional Circulation Models

Uncertainty

Coastal forcing models

BIAS CORRECTION



Impact models

# Statistical downscaling method

ATMOSPHERIC CIRCULATION
(predictor X: SLP)

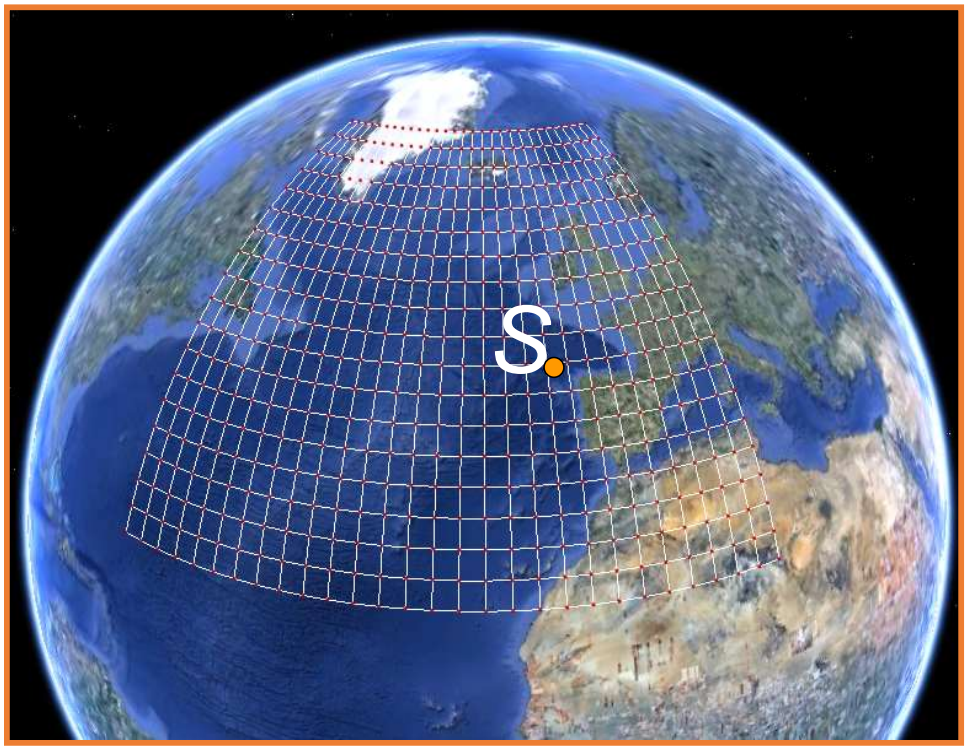
MULTIVARIATE WAVE CLIMATE
(predictand Y, H, T, Dir)

*Regional atmospheric climatology (X)*

*Local wave climatology (Y)*

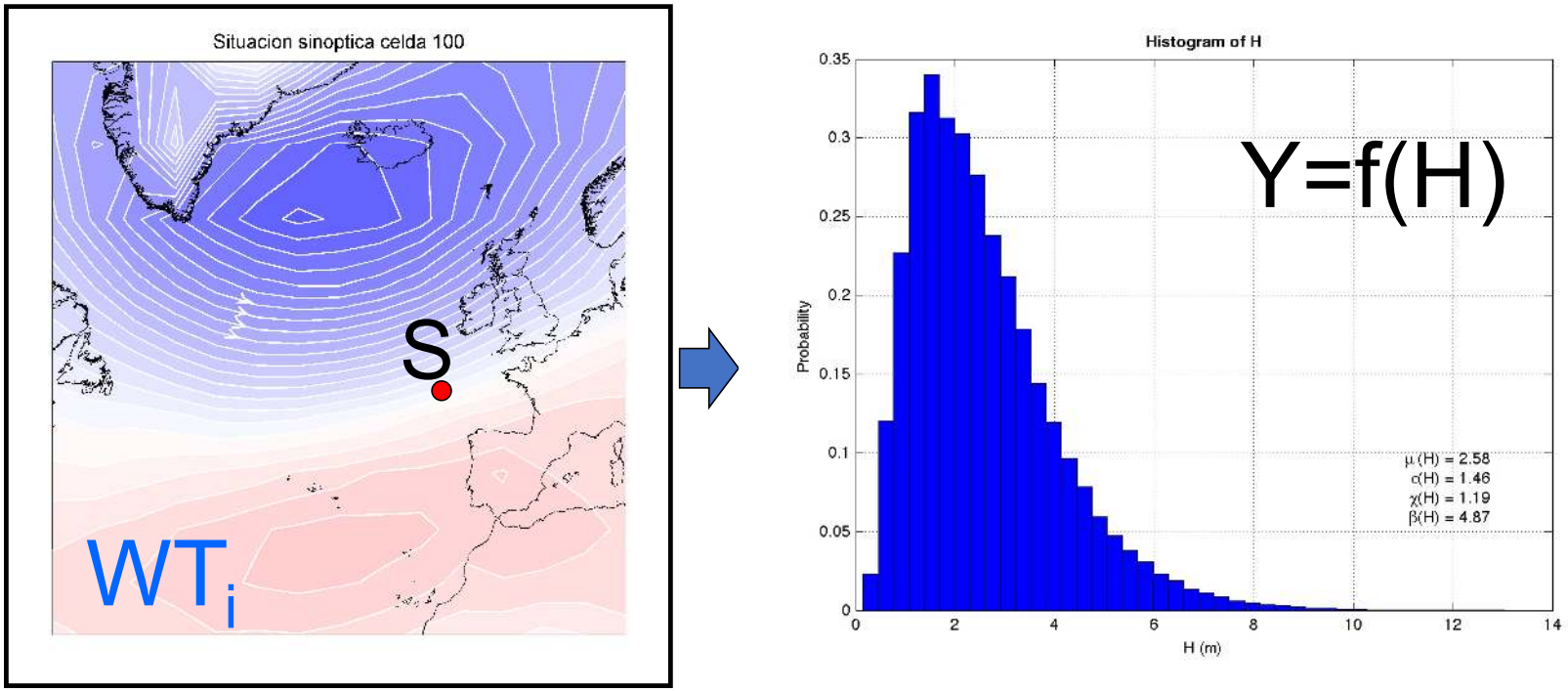
# Statistical downscaling method

Predict multivariate wave climate (Y) at a particular location *S* as a function of synoptic atmospheric circulation (X)



# Statistical downscaling method based on weather types

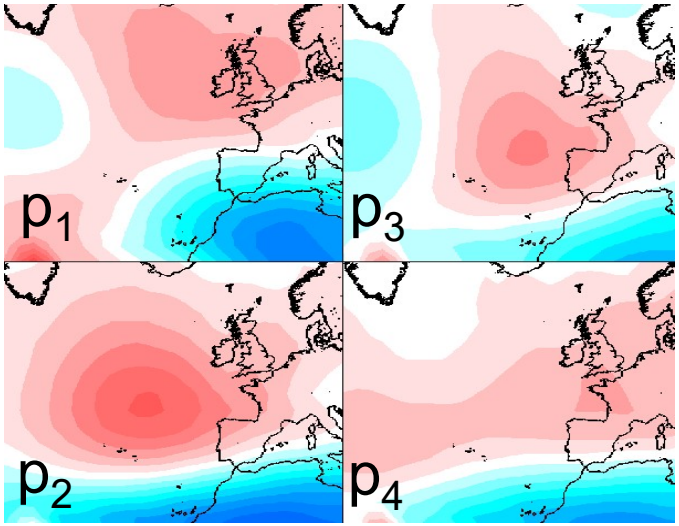
Predict multivariate wave climate (Y) at a particular location *S* as a function of Synoptic Atmospheric Circulation patterns (X)

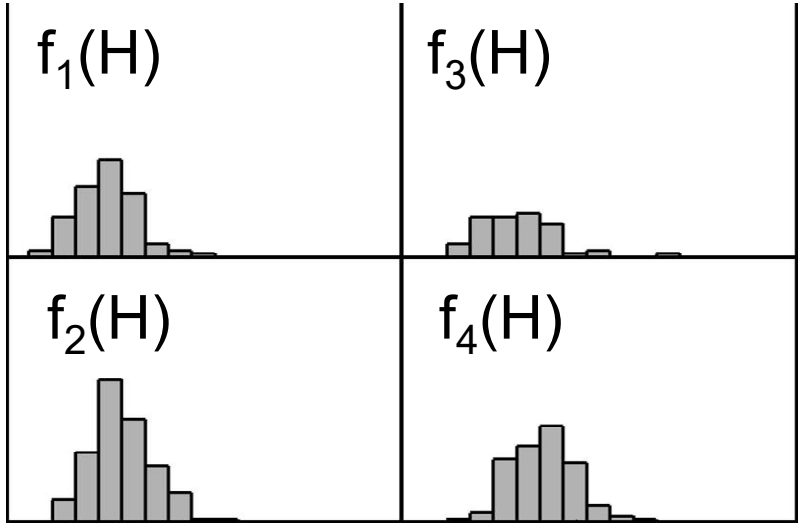



WT= Weather-type (Circulation Type)

## Statistical downscaling method based on weather types

$X=(WT_1,WT_2,WT_3,WT_4)$ Y

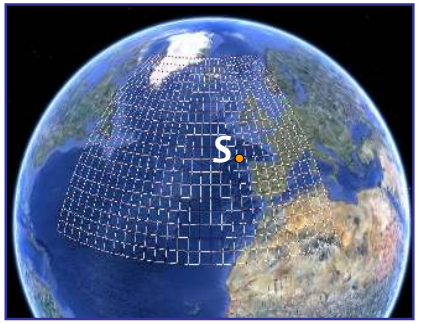



$p_i$=ocurrence probability of $WT_i$

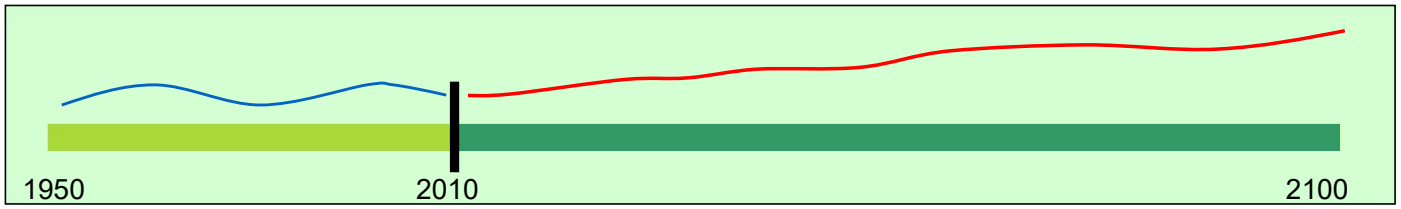
$p_1+p_2+p_3+p_4=1$

$f_S(H)=p_1f_1(H)+p_2f_2(H)+p_3f_3(H)+p_4f_4(H)$

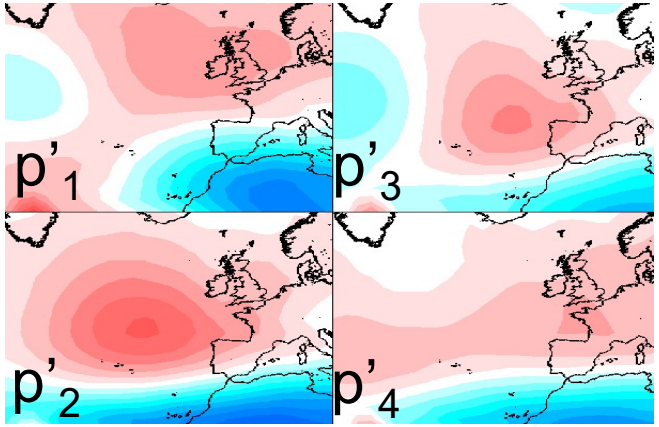


# Statistical downscaling method based on weather types

Project multivariate wave climate (Y) at a particular location *S* for a given GCM in a given time slice (X')




X'=new predictor



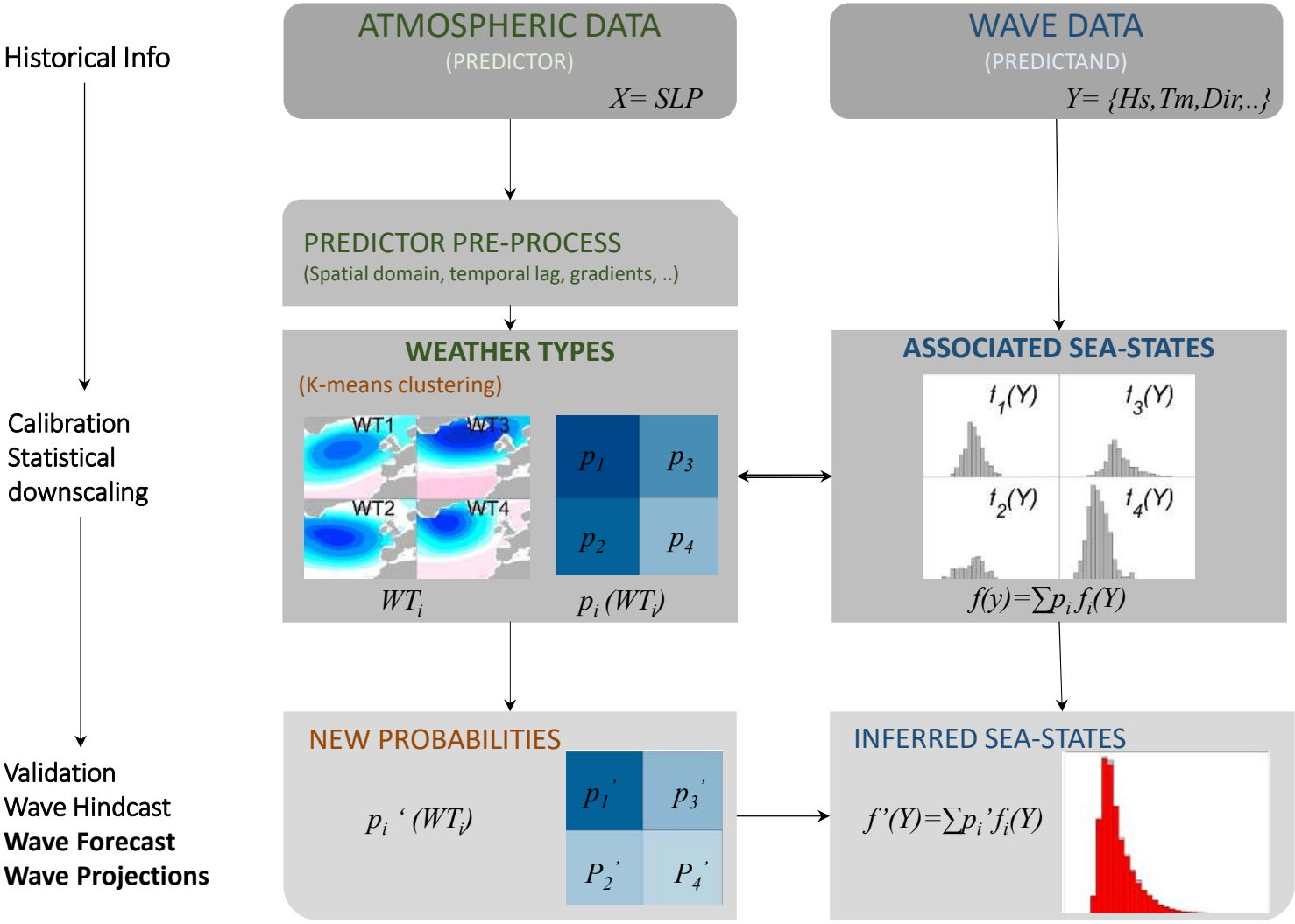

$$Y = g(X')$$

$$p'_1+p'_2+p'_3+p'_4=1$$

$$f'_S(H)=p'_1f_1(H)+p'_2f_2(H)+p'_3f_3(H)+p'_4f_4(H)$$

$$df(H)=f'_S(H)-f_S(H)$$

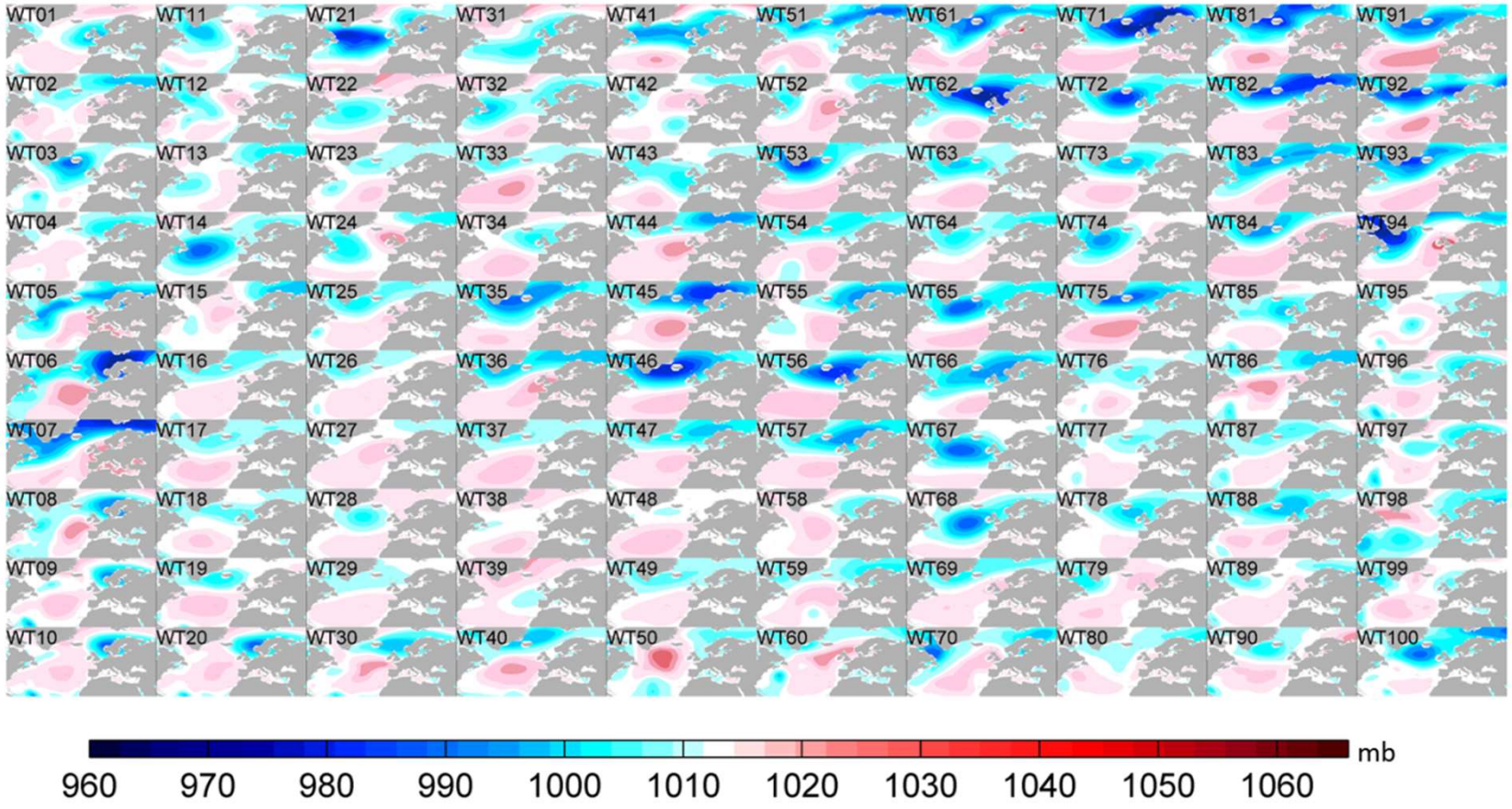
# Statistical downscaling method based on weather types




Camus et al., 2014

# Statistical downscaling method based on weather types
# WAVE PROJECTIONS over Europe

WEATHER TYPE CLASSIFICATION using KMA

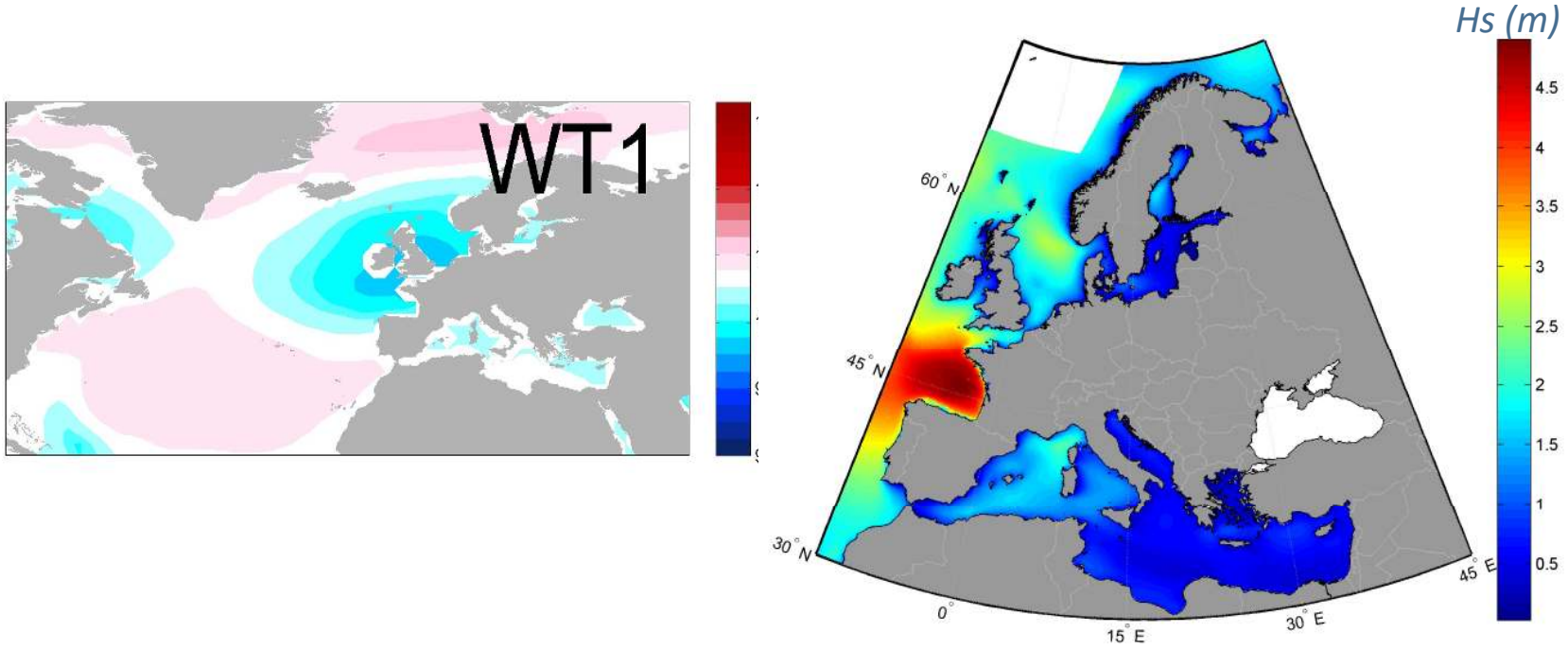



Perez, J., Menendez, M., Camus, P., Mendez, F.J., Losada, I.J. Statistical multi-model climate projections of surface ocean waves in Europe (2015). Ocean Modelling, DOI: 10.1016/j.ocemod.2015.06.001

# Statistical downscaling method based on weather types
# WAVE PROJECTIONS over Europe

***Relationship between the weather types and multivariate wave climate***

*Predictor **X (WT)*** ⟶ *Predictand **Y** (hs, tm, FE, …)*

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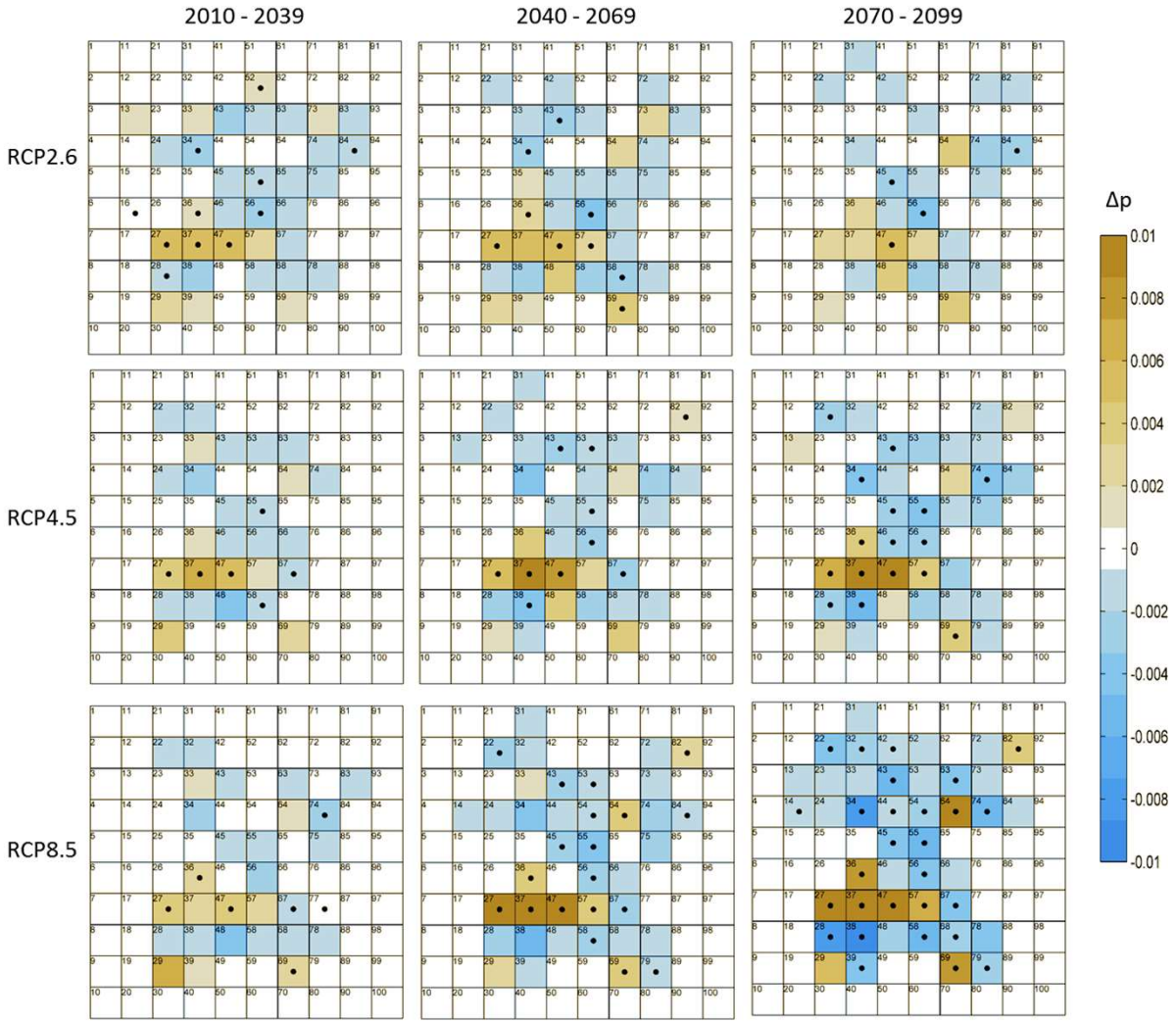
# Statistical downscaling method based on weather types

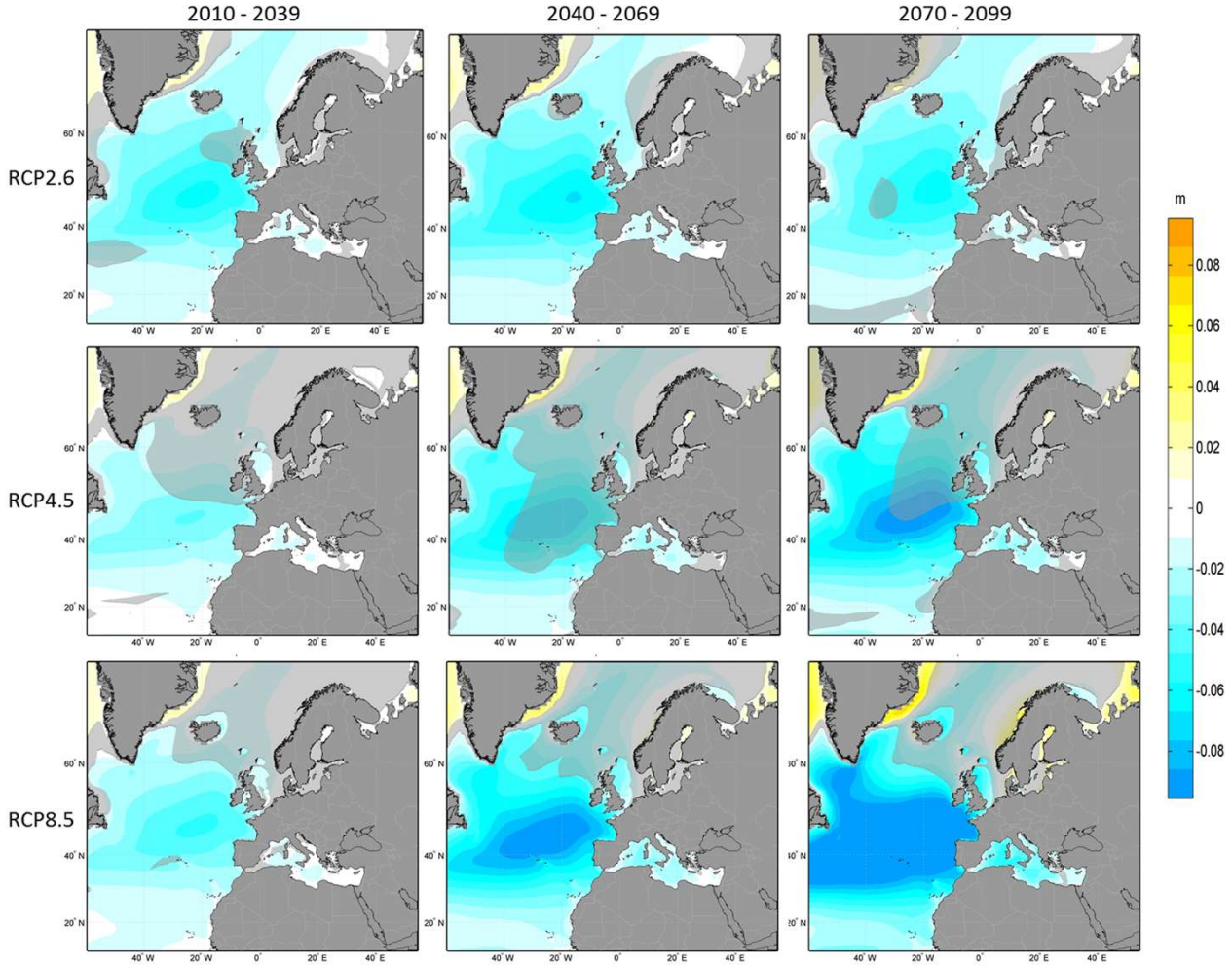
CHANGES IN THE WTS




***Changes with respect to the control period (1975-2004)***

Perez, J., Menendez, M., Camus, P., Mendez, F.J., Losada, I.J. Statistical multi-model climate projections of surface ocean waves in Europe (2015). Ocean Modelling, DOI: 10.1016/j.ocemod.2015.06.001

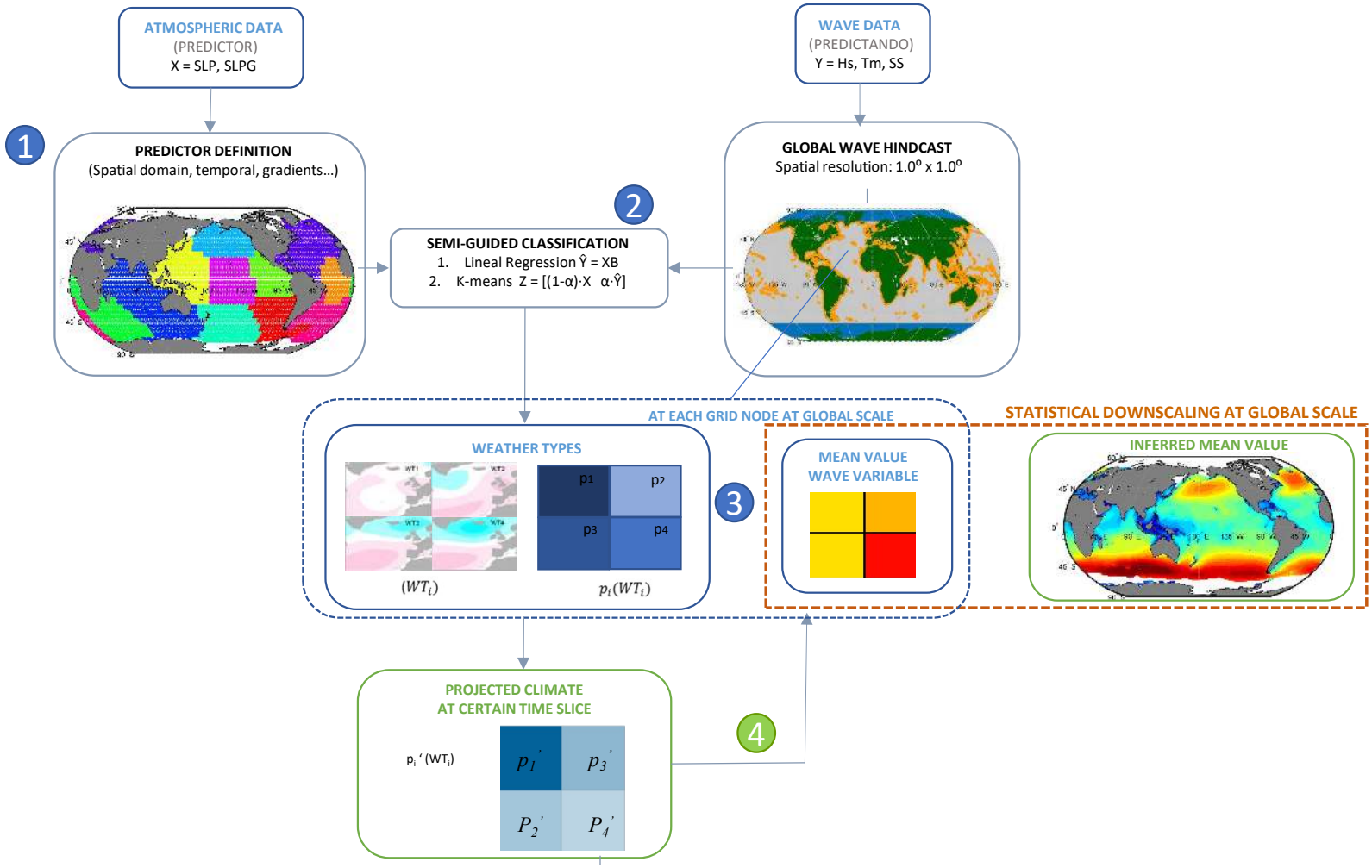
# Statistical downscaling method based on weather types
# WAVE PROJECTIONS over Europe




***Changes in Hs with respect to the control period (1975-2004)***

Perez, J., Menendez, M., Camus, P., Mendez, F.J., Losada, I.J. Statistical multi-model climate projections of surface ocean waves in Europe (2015). Ocean Modelling, DOI: 10.1016/j.ocemod.2015.06.001

# Statistical downscaling method based on weather types
# GLOBAL WAVE PROJECTIONS

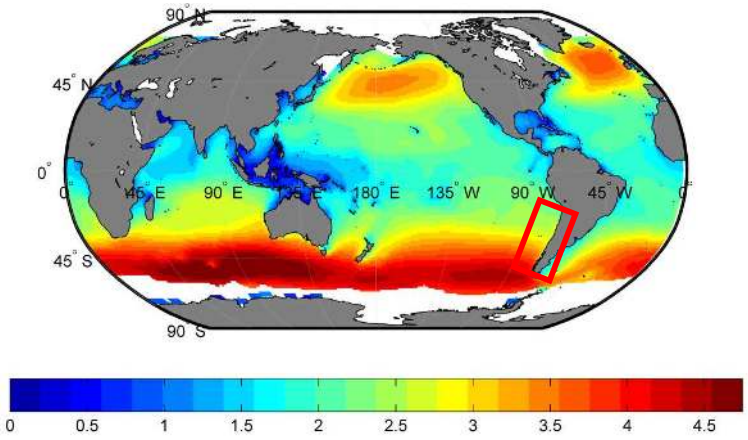



More details in Camus et al., 2014; Pérez et al., 2015; Camus et al., 2017

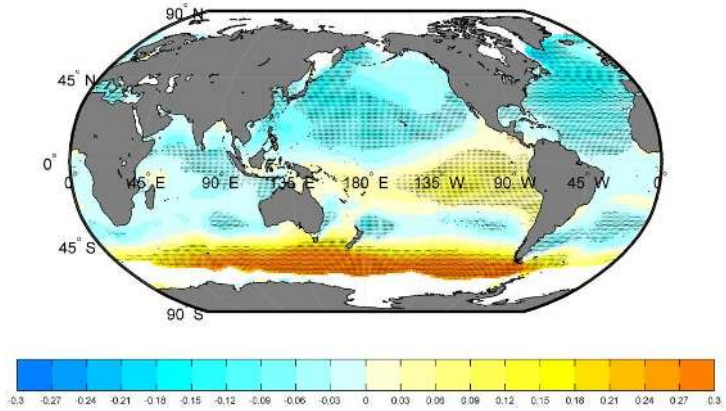
# Statistical downscaling method based on weather types
# GLOBAL WAVE PROJECTIONS

PROJECTED CHANGES in Hs
Scenario RCP8.5
Multi-model Ensemble (40 GCMs)
For the period **2070-2099**
Relative to the period 1979-2005

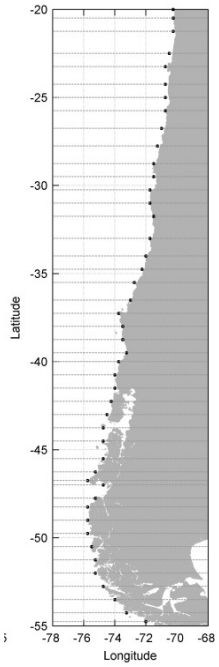
Multi-model annual mean Hs (m)
(1979-2005)

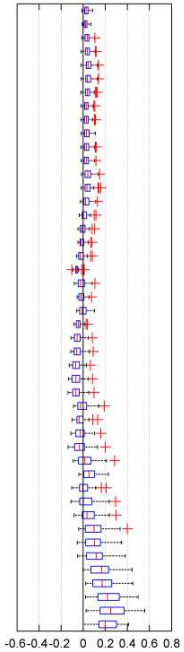



Multi-model changes annual Hs

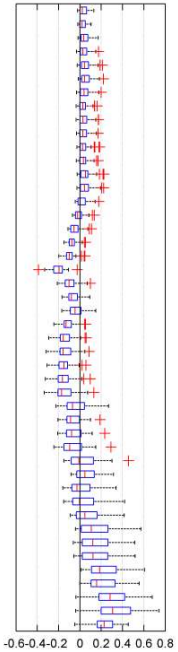



## Regional Projections

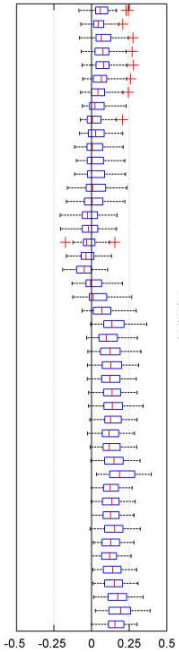


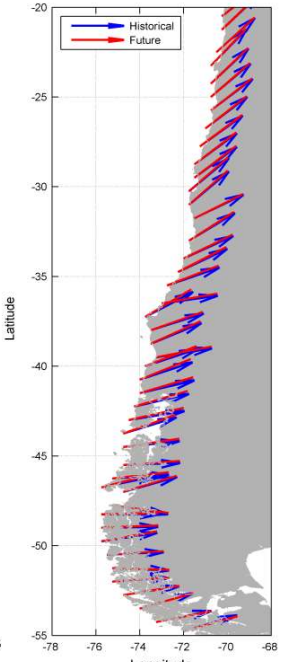

Changes Hs



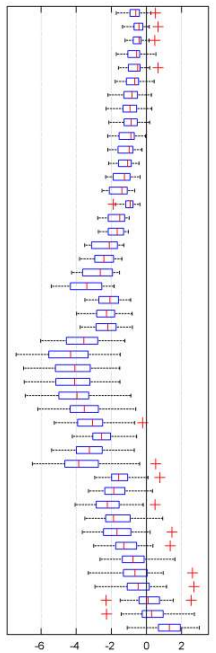

Changes p95 Hs




Changes Tp




Direction

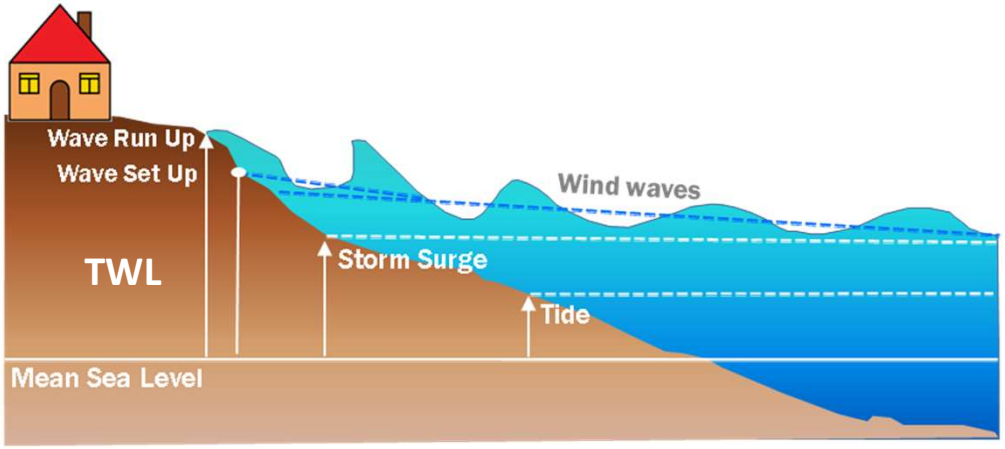


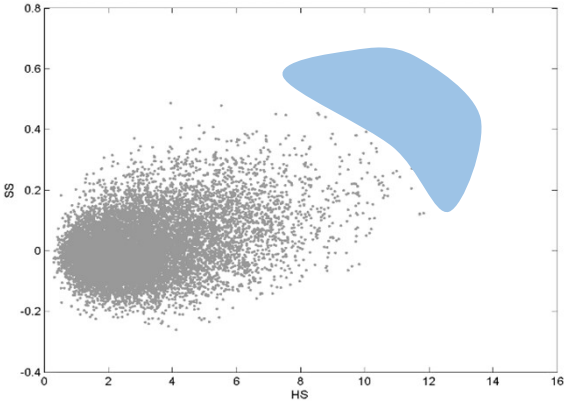

Changes Direction

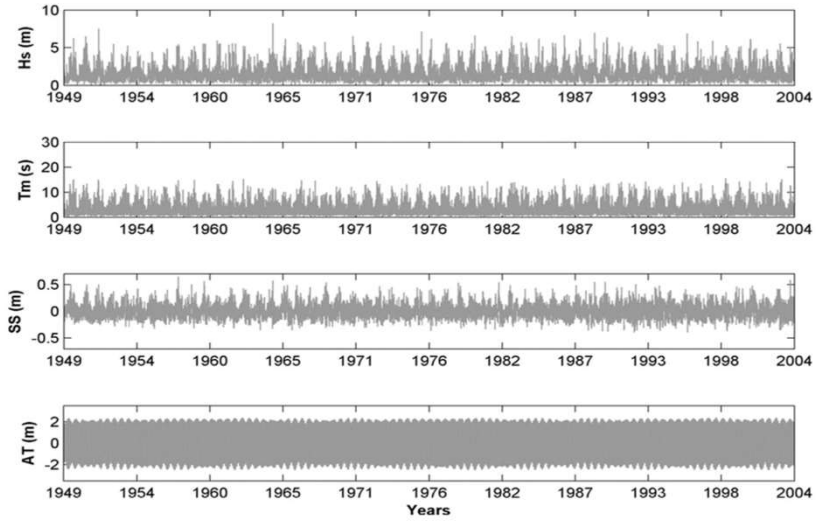
The first coordinated multivariate ensemble of 21st Century global wind-wave climate projections: **COWCLIP 2.0**

Morim et al., 2019, Morim et al., 2020

# CLIMATE EMULATORS based on weather types
# COASTAL FLOODING



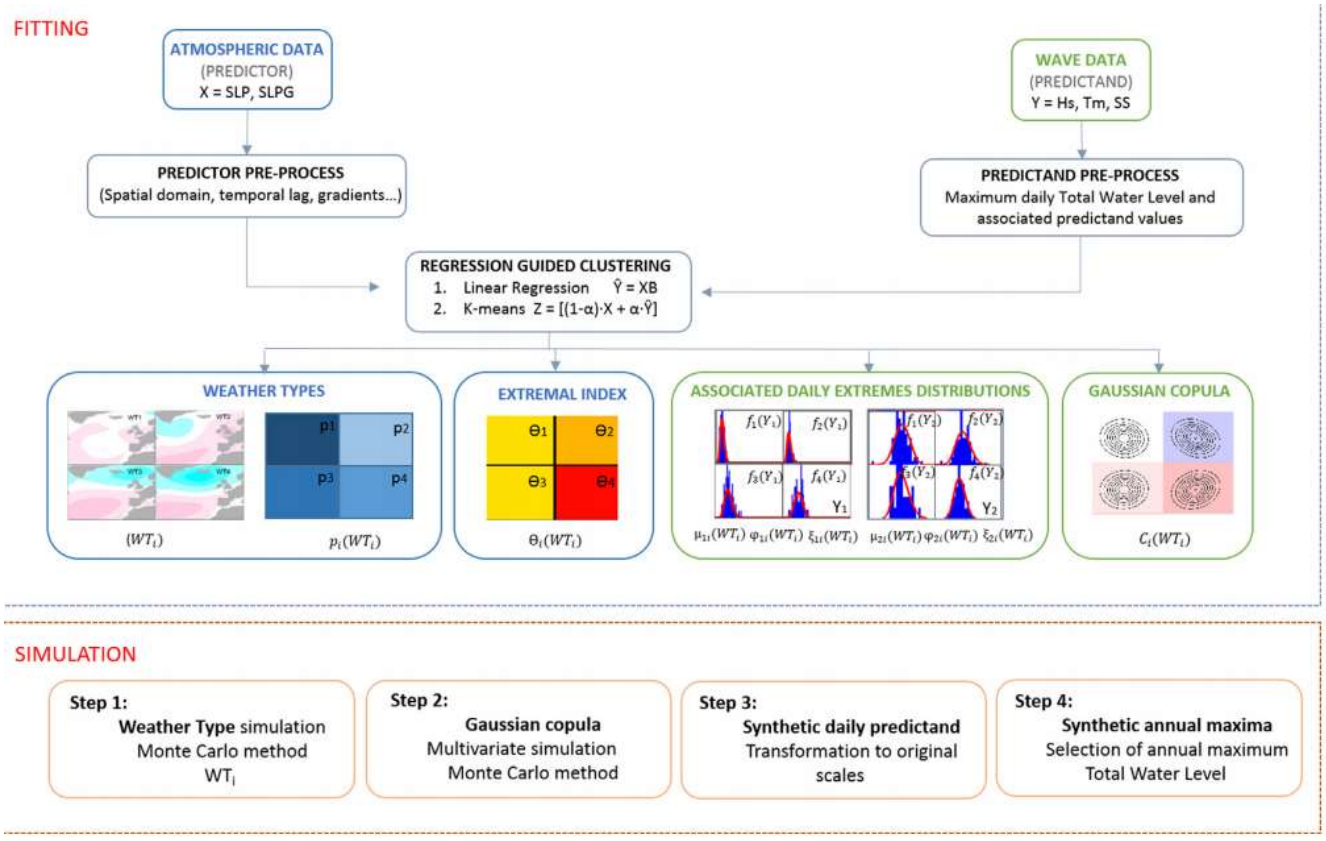

OBJECTIVES:

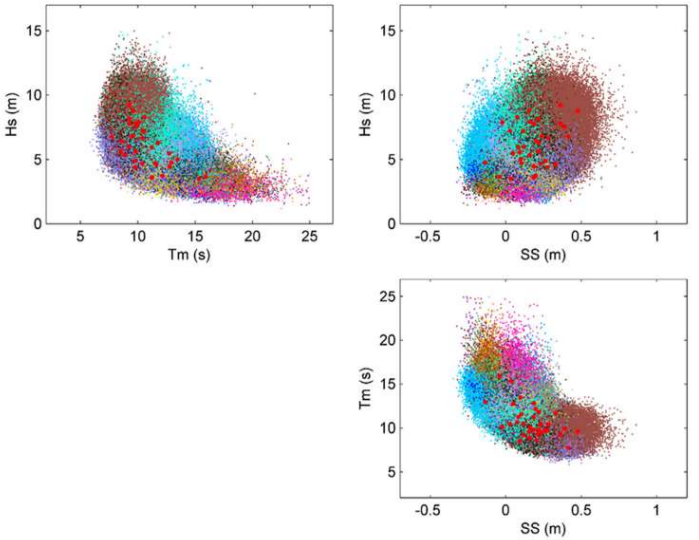
- Increase the population of multivariate extremes multivariados
- Probabilistic characterization of the coastal flooding impact

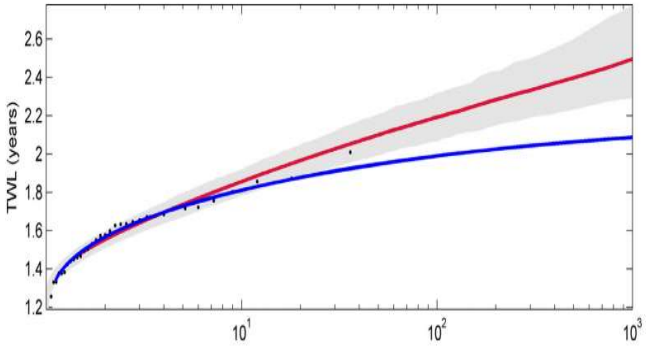
1) Modelling the dependence between multiple variables (COPULAS models)

2) Linked to climate variability

# CLIMATE EMULATORS based on weather types
# COASTAL FLOODING

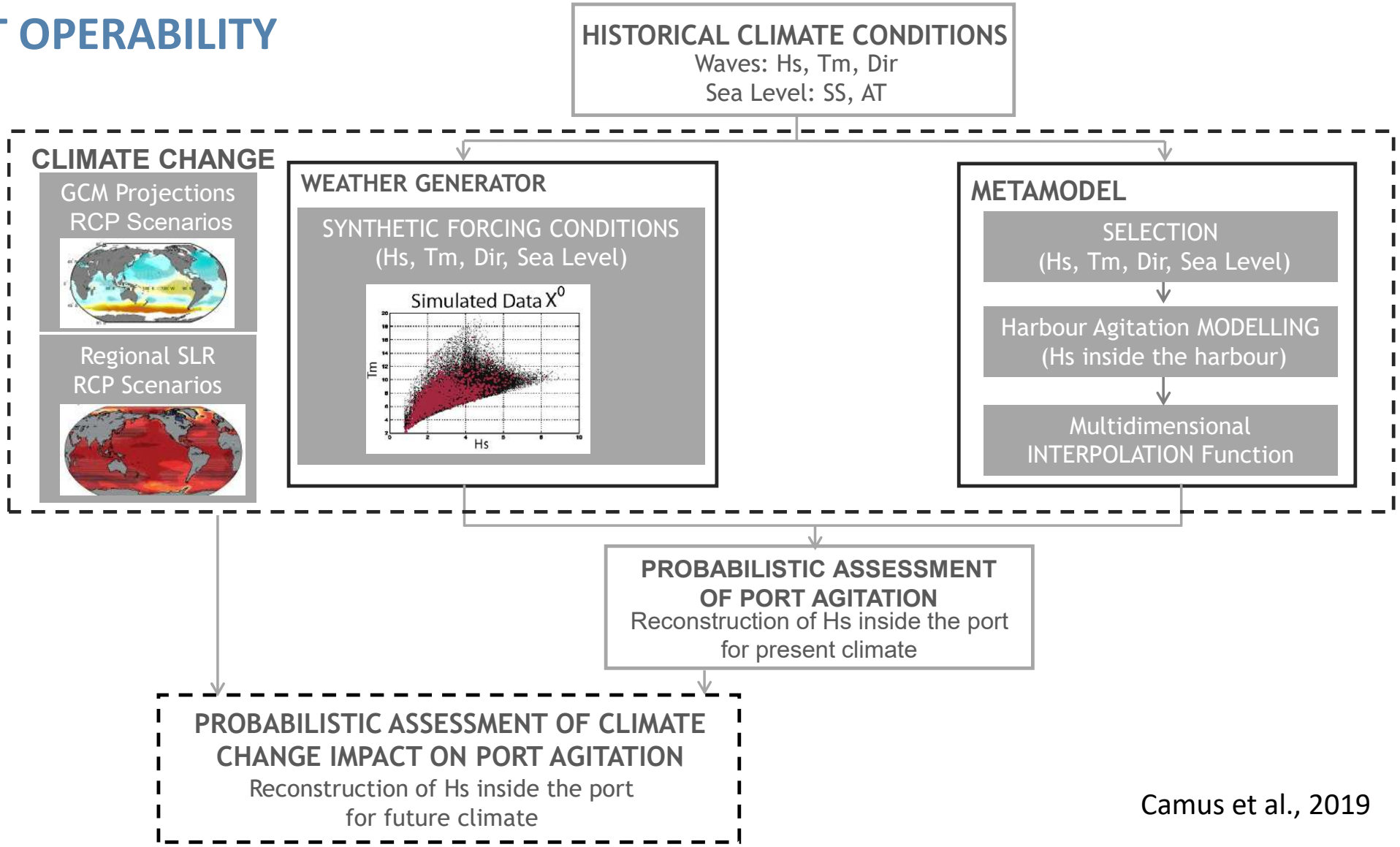


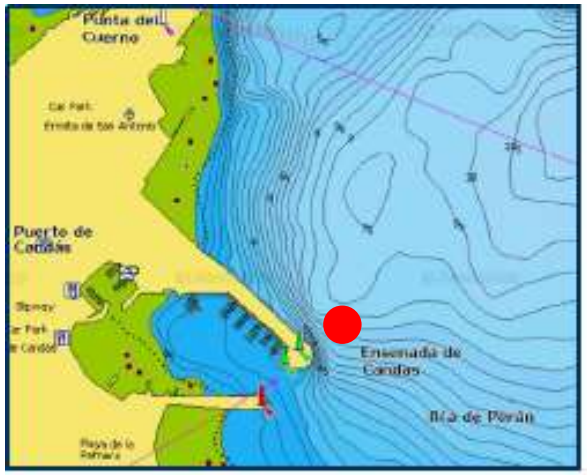

Rueda et al., 2016

# CLIMATE EMULATORS based on weather types
# PORT OPERABILITY

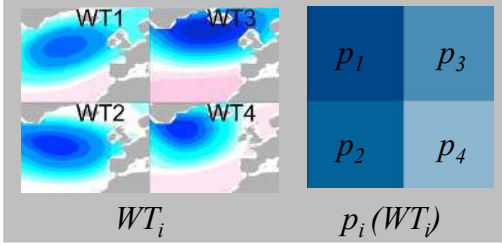



Camus et al., 2019

# CLIMATE EMULATORS based on weather types
# PORT OPERABILITY

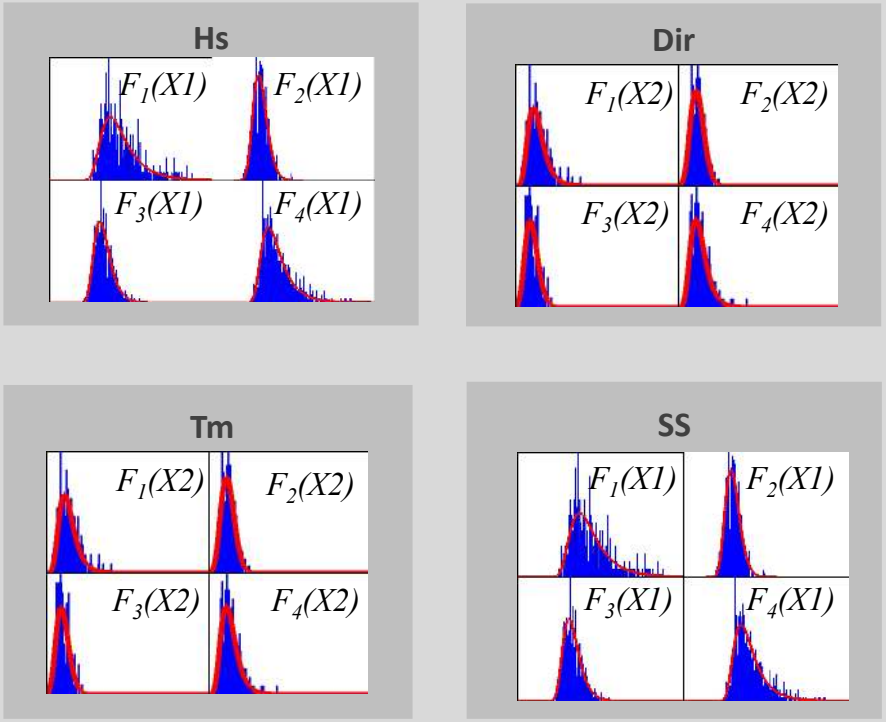



**1 WEATHER TYPES (WTs) (K-means)**

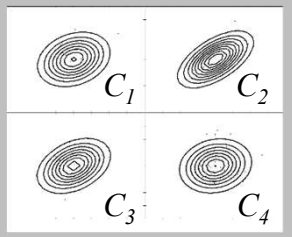



$WT_i$ $p_i(WT_i)$

**MARGINAL DISTRIBUTIONS** 2




**3 MULTIVARIATE DISTRIBUTION GAUSSIAN COPULAS**




**4 SYNTHETIC GENERATION OF MULTIVARIATE DATA**

Camus et al., 2019

# METAMODEL – hybrid downscaling
# PORT OPERABILITY

Synthetic Forcing Conditions
Waves: Hs, Tm, Dir
Sea Level: SS, AT

↓

SELECTION
(Hs, Tm, Dir, Sea Level)

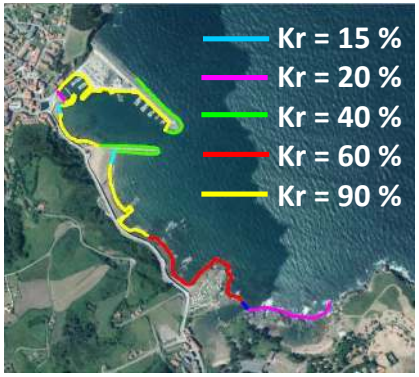
↓

Harbour Agitation Model
(Hs inside the harbour)

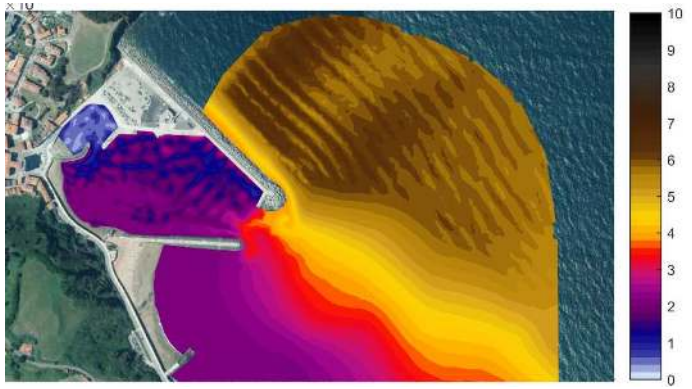
↓

Reconstruction of Hs inside the port
Probabilistic Assessment of Port Agitation

Low and mean tide

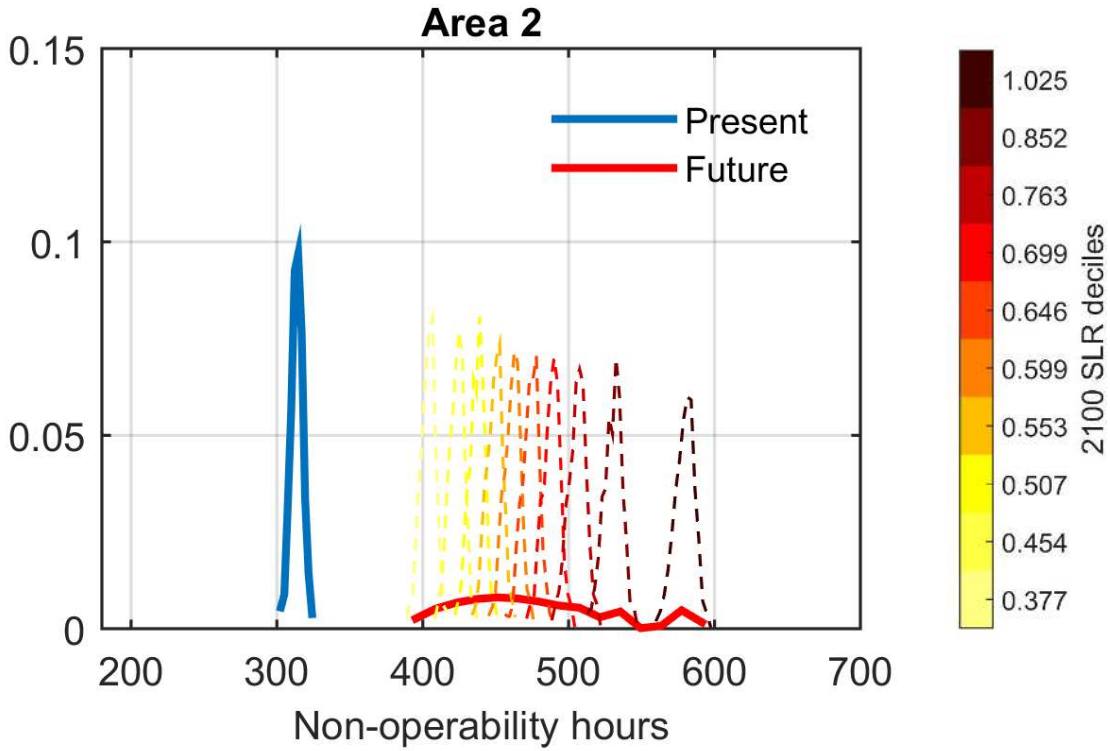



High tide




MSP: Díaz-Hernández et al., 2015

# CLIMATE EMULATORS based on weather types
# PORT OPERABILITY


**PROBABILISTIC SEA LEVEL RISE SCENARIOS**

Present Climate: 1960-2010

Future Climate: 2050-2100

Camus et al., 2019

# CLIMATE CHANGE RISK TO GLOBAL PORT OPERATION

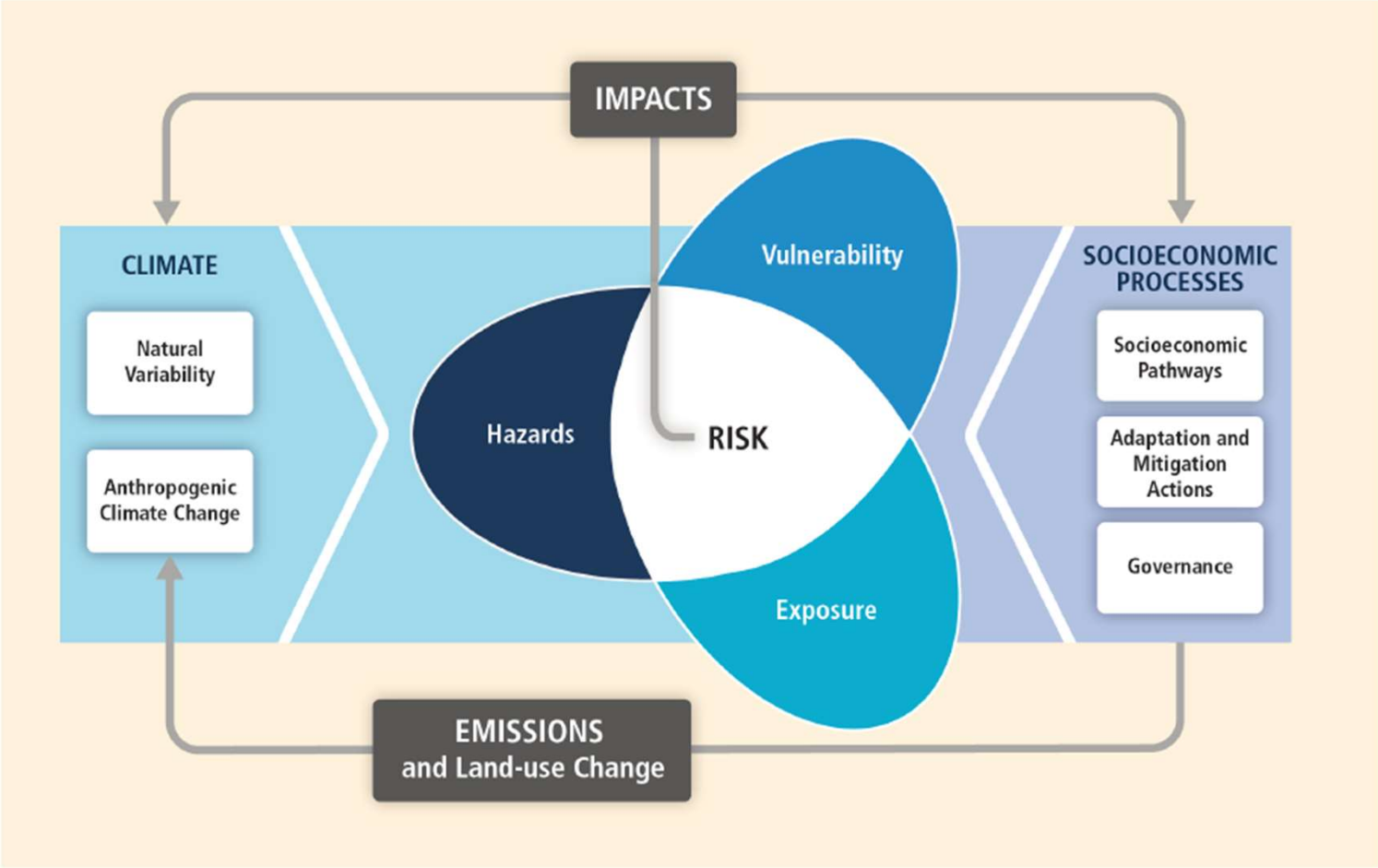
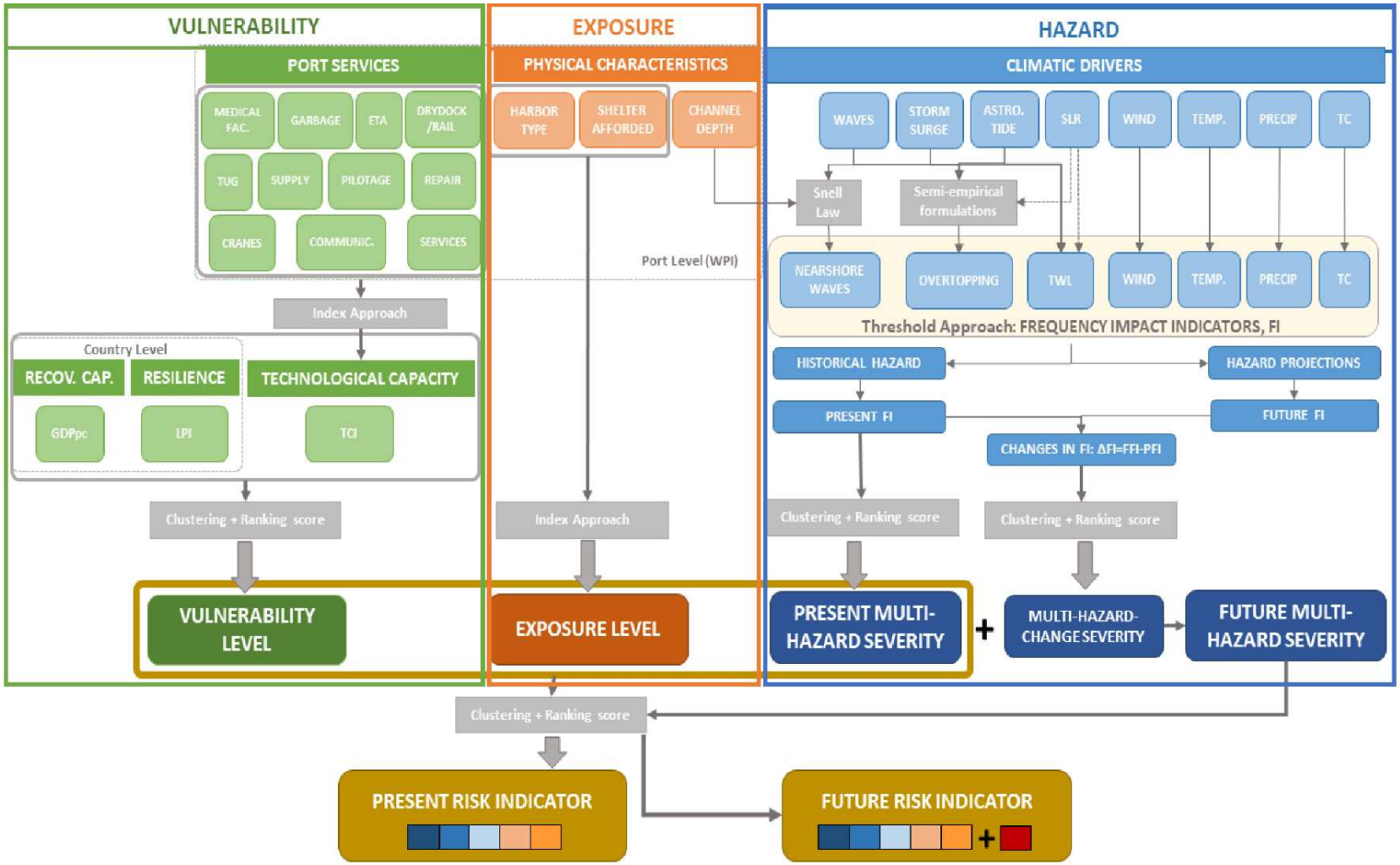


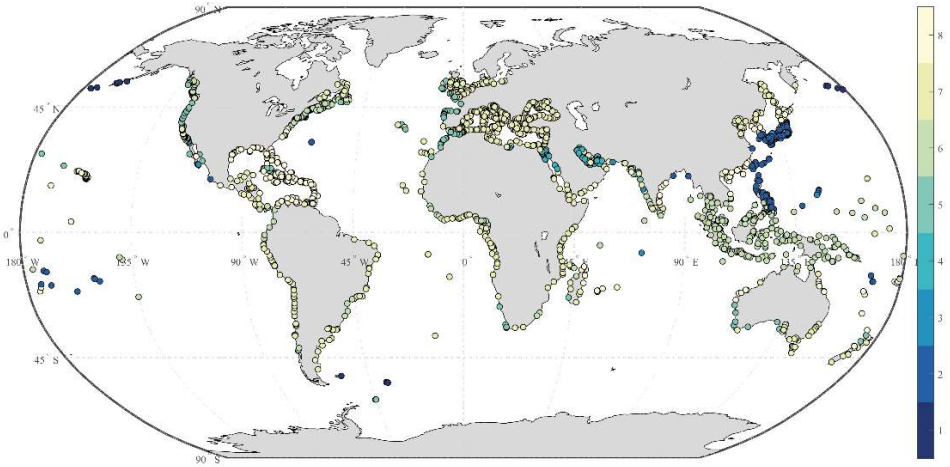

Figure SPM.1.

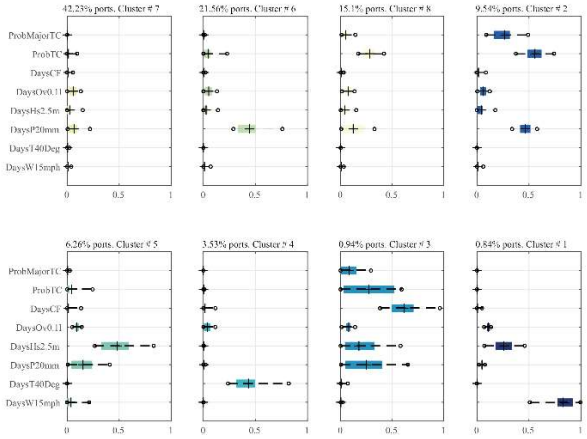
# CLIMATE CHANGE RISK TO GLOBAL PORT OPERATION

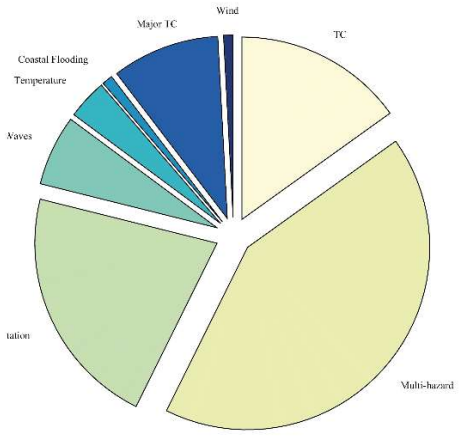


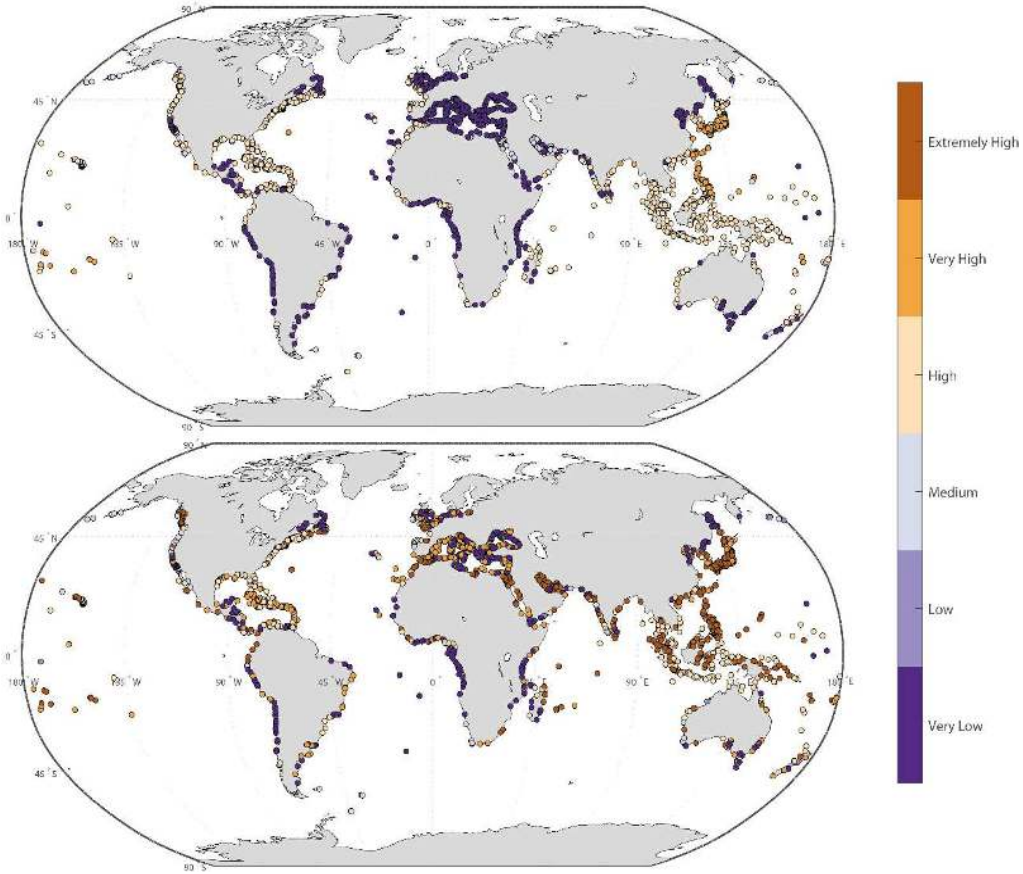

Izaguirre et al., 2020

# CLIMATE CHANGE RISK TO GLOBAL PORT OPERATION



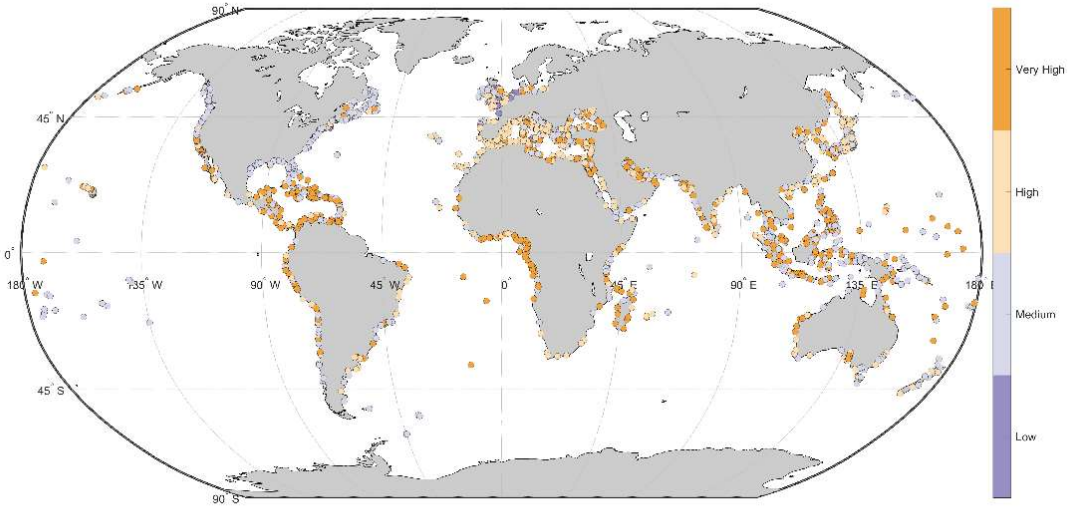


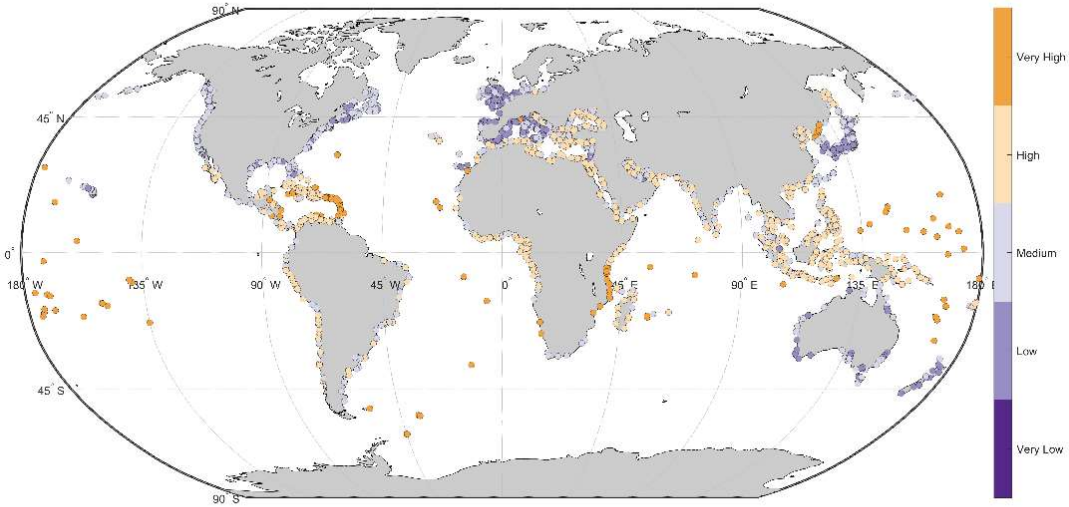




Izaguirre et al., 2020

# CLIMATE CHANGE RISK TO GLOBAL PORT OPERATION




Vulnerability level

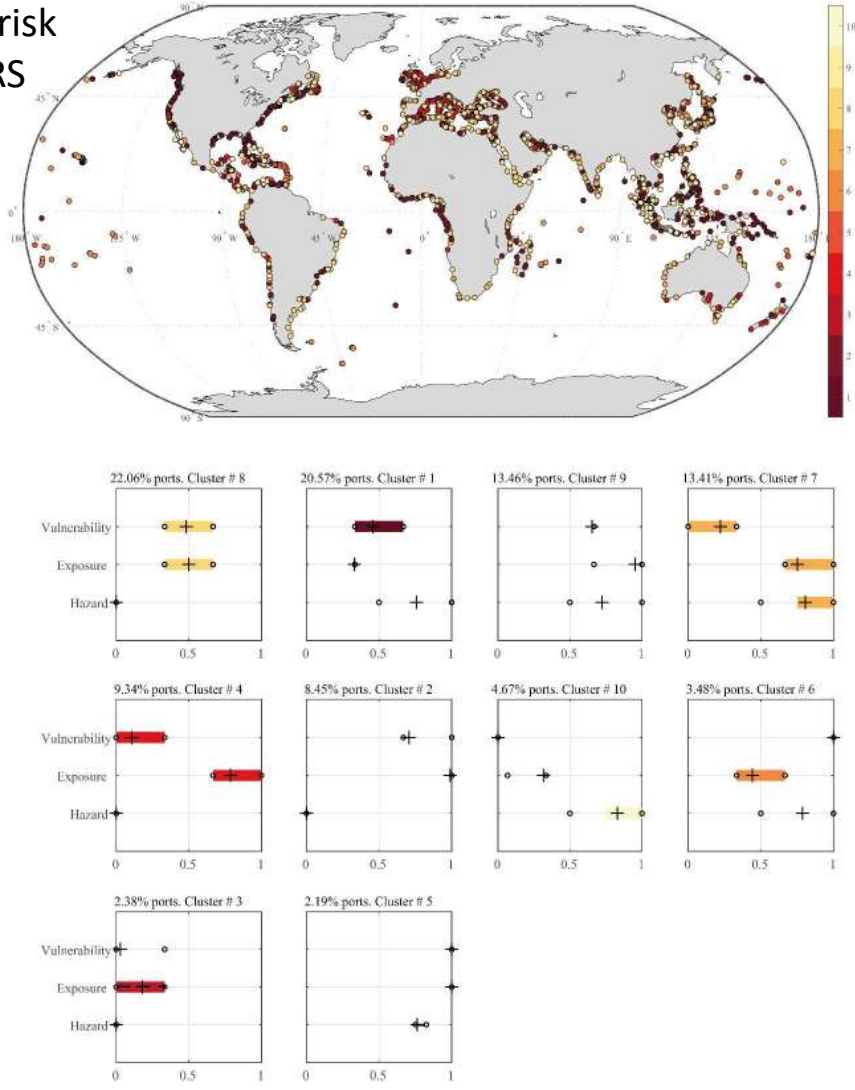



Exposure level

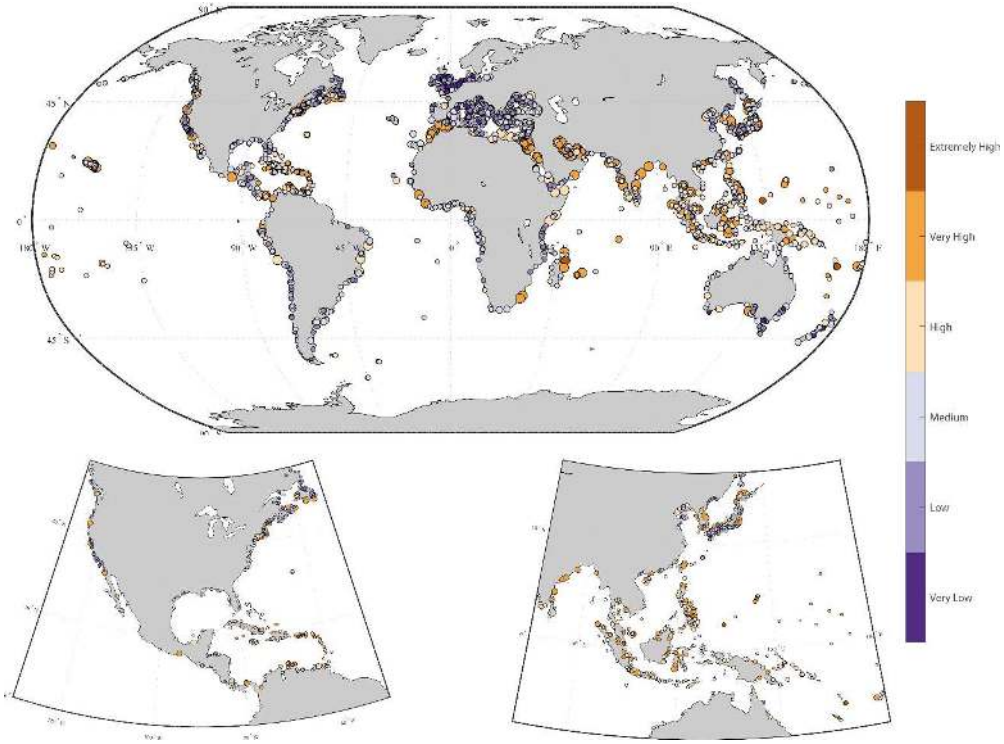
Izaguirre et al., 2020

# CLIMATE CHANGE RISK TO GLOBAL PORT OPERATION

Present risk
CLUSTERS

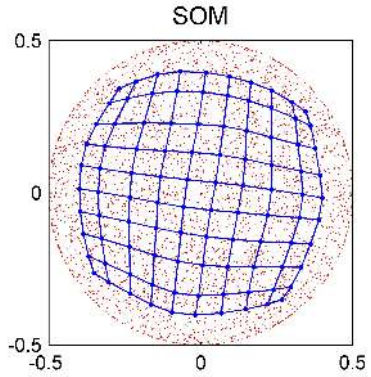


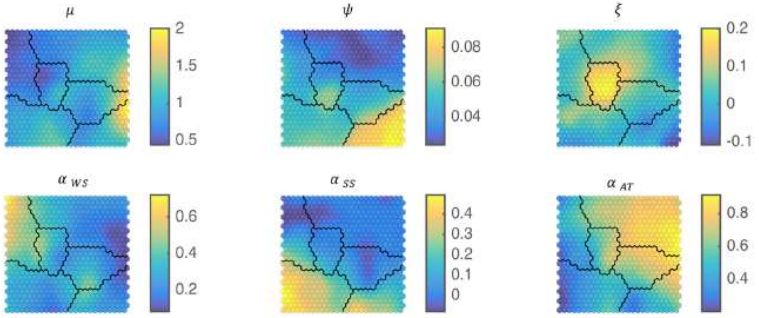

Climate risk
LEVELS

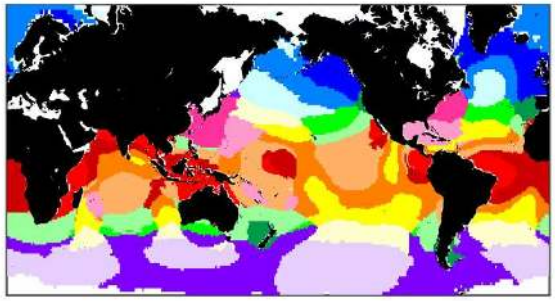



Izaguirre et al., 2020

# Summary



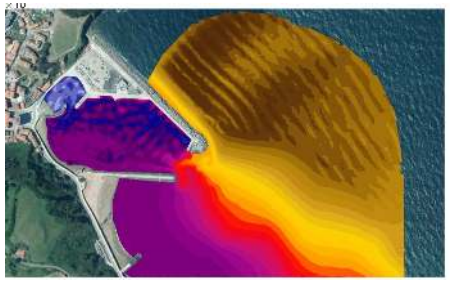



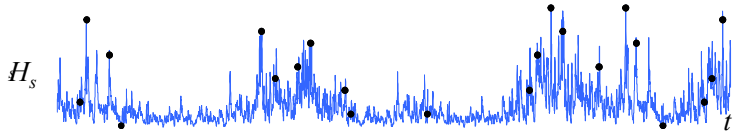
**METAMODEL**

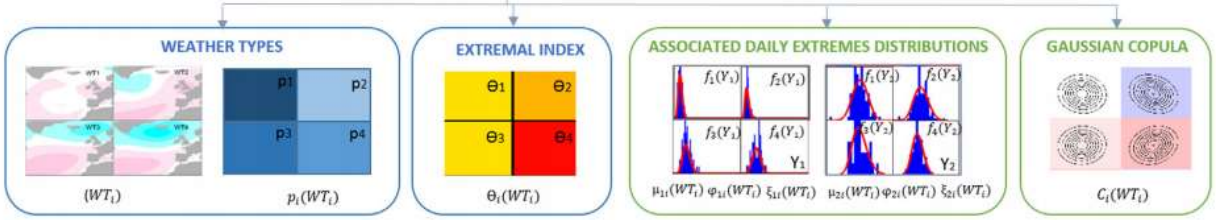
SELECTION
(Hs, Tm, Dir, Sea Level)

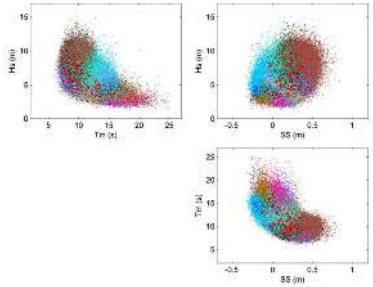
Harbour Agitation MODELLING
(Hs inside the harbour)

Multidimensional
INTERPOLATION Function





# Applications of data science in coastal engineering

**Paula Camus**

MASCOT-NUM 2021

28TH-30TH April