Desarrollo de metodologías para el análisis de tendencias del clima marítimo: Aplicación al litoral español

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"Effects of the climate change on the spanish coast"(2002-2004)

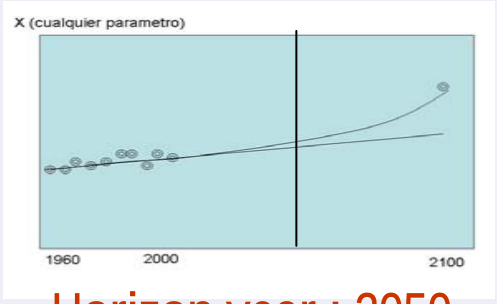
Funded by the Spanish Agency of Climate Change
(Ministerio de Medio Ambiente, SPAIN)

MINISTERIO DE MEDIO AMBIENTE

Phase I: To evaluate wave climate and sea level changes along the littoral

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Phase III: To establish strategies



Horizon year : 2050

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IC3

	4T 2002	1T 2003	2T 2003	3T 2003	4T 2003	1T 2004	2T 2004	3T 2004	4T 2004	1T 2005
Fase I: Evaluación de cambios en la dinámica costera española	Recopilación información	Análisis datos históricos de oleaje, nivel y mareas (1950-2000)	Fase Ia. Recopilación de información	Fase Ib. Análisis datos olas, nivel	Análisis datos de predicción para escenarios IPCC: olas,nivel, caudal Análisis datos históricos de caudal fluvial y sedimento Zonificación de zonas homogéneas Fase Ic. Evolución histórica en la dinámica costera en el siglo XX	Fase Id. Prognosis de cambio en la dinámica costera para escenarios CC				
Fase II: Evaluación de efectos en la costa española			Efectos teóricos en las obras: Fiabilidad, operatividad Efectos teóricos en las playas y dunas Efectos teóricos en estuarios, deltas, humedales, lagunas	Fase IIa. Efectos teóricos del cambio climático en el litoral	Análisis efectos en las zonas homogéneas	Estudios de detalle Fase IIb. Efectos en las zonas homogéneas del litoral español	Fase IIc. Estudios de detalle			
Fase III: Establecimiento de políticas y estrategias						Propuesta de indicadores e índices Integración resultados en base de datos del inventario para la GIZC Integración de indicadores en el SIG de la GIZC			Fase IIIa. Documento Técnico Fase IIIb. Documento Gestores Costa	

1. Motivation

What should be the size of the blocks of this rubblemound breakwater?

1. Motivation

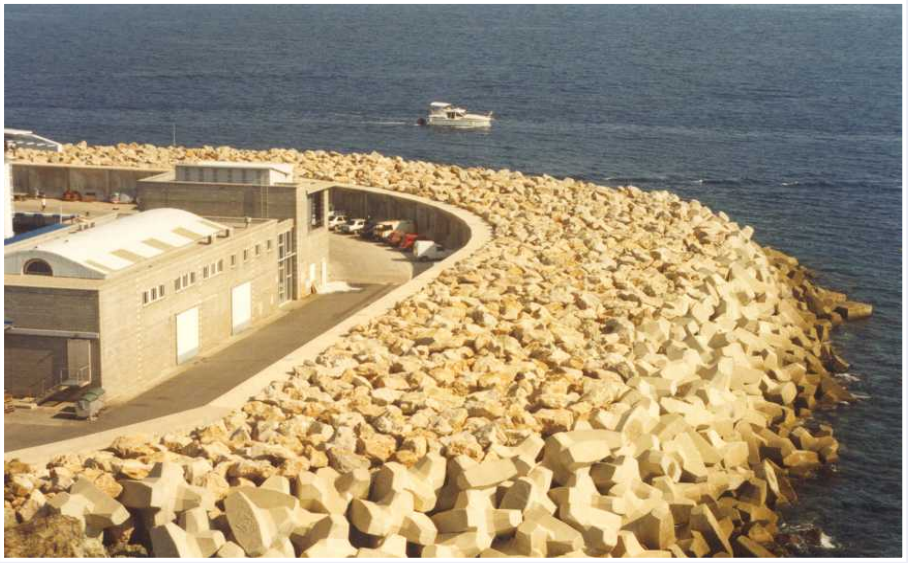
How many hours in a year the agitation inside the harbor is higher than 30 cm?

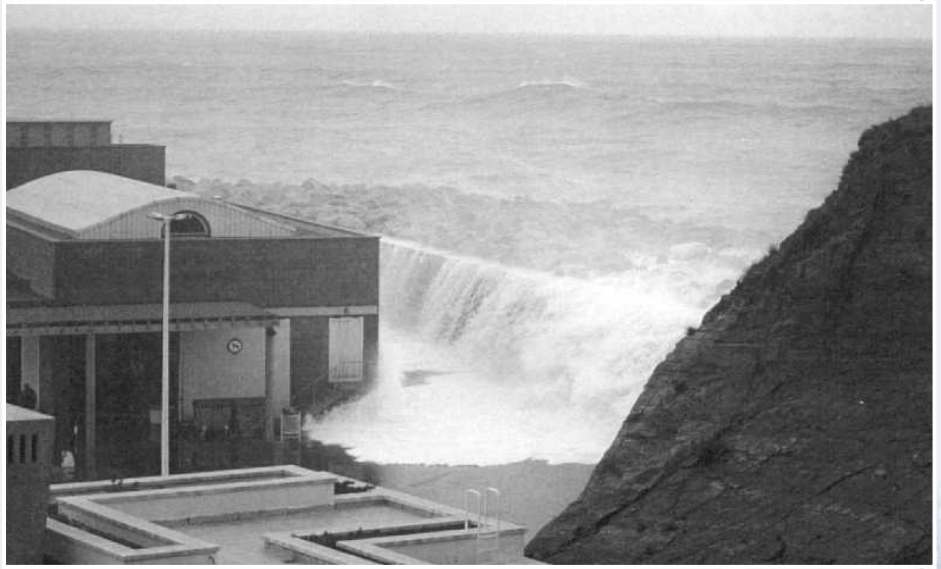
1. Motivation

How frequent does the breaching of this beach take place?

1. Motivation

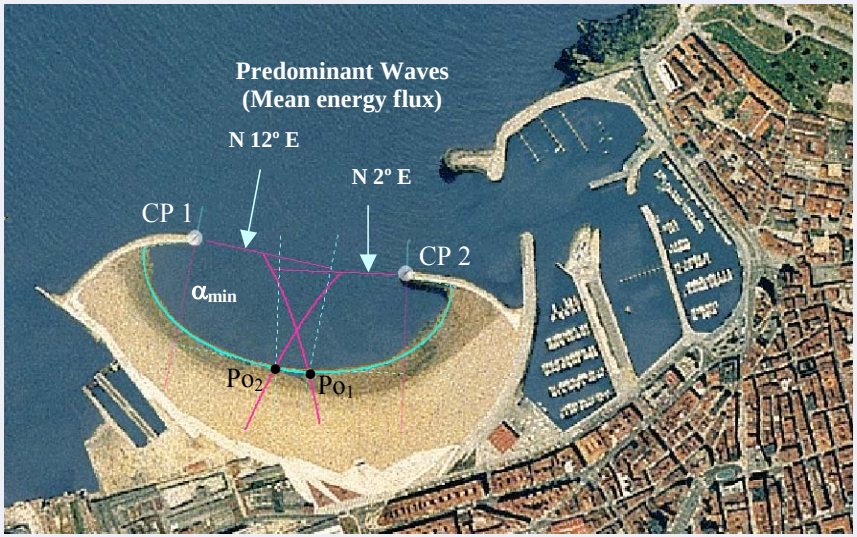
How often is the overtopping in this breakwater?

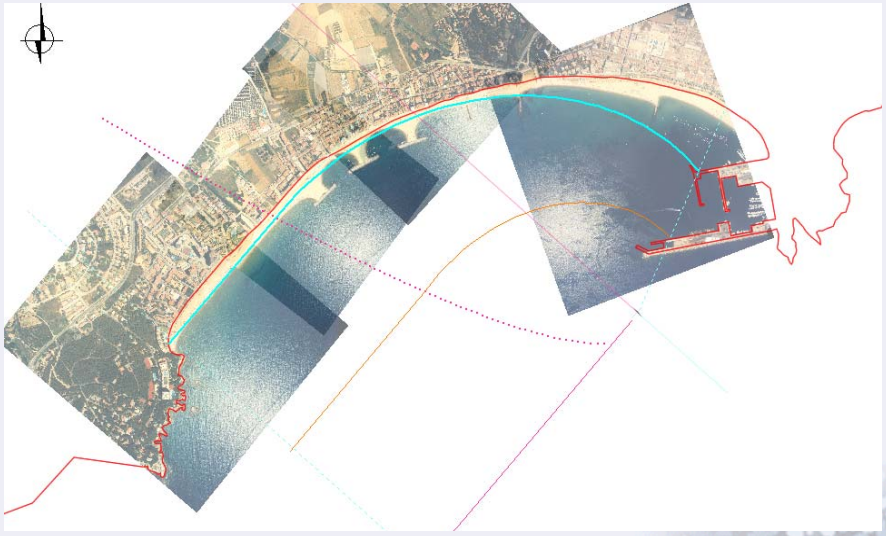




1. Motivation

Which is the shape of the equilibrium planform of these beaches?





1. Motivation

How do we estimate littoral sediment transport?

1. Motivation

What should be the size of the blocks of this rubblemound breakwater?

How many hours in a year the agitation is higher than 30 cm inside the harbor?

How frequent does the breaching of this beach take place?

How often is the overtopping in this breakwater?

Which is the shape of the equilibrium planform of these beaches?

How do we estimate littoral sediment transport?

…

We need to determine wave climate at a particular site, obtaining long-term and long-term extreme value statistics of some sea state parameters

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CONCEPTOS

Oleaje

Bases de datos

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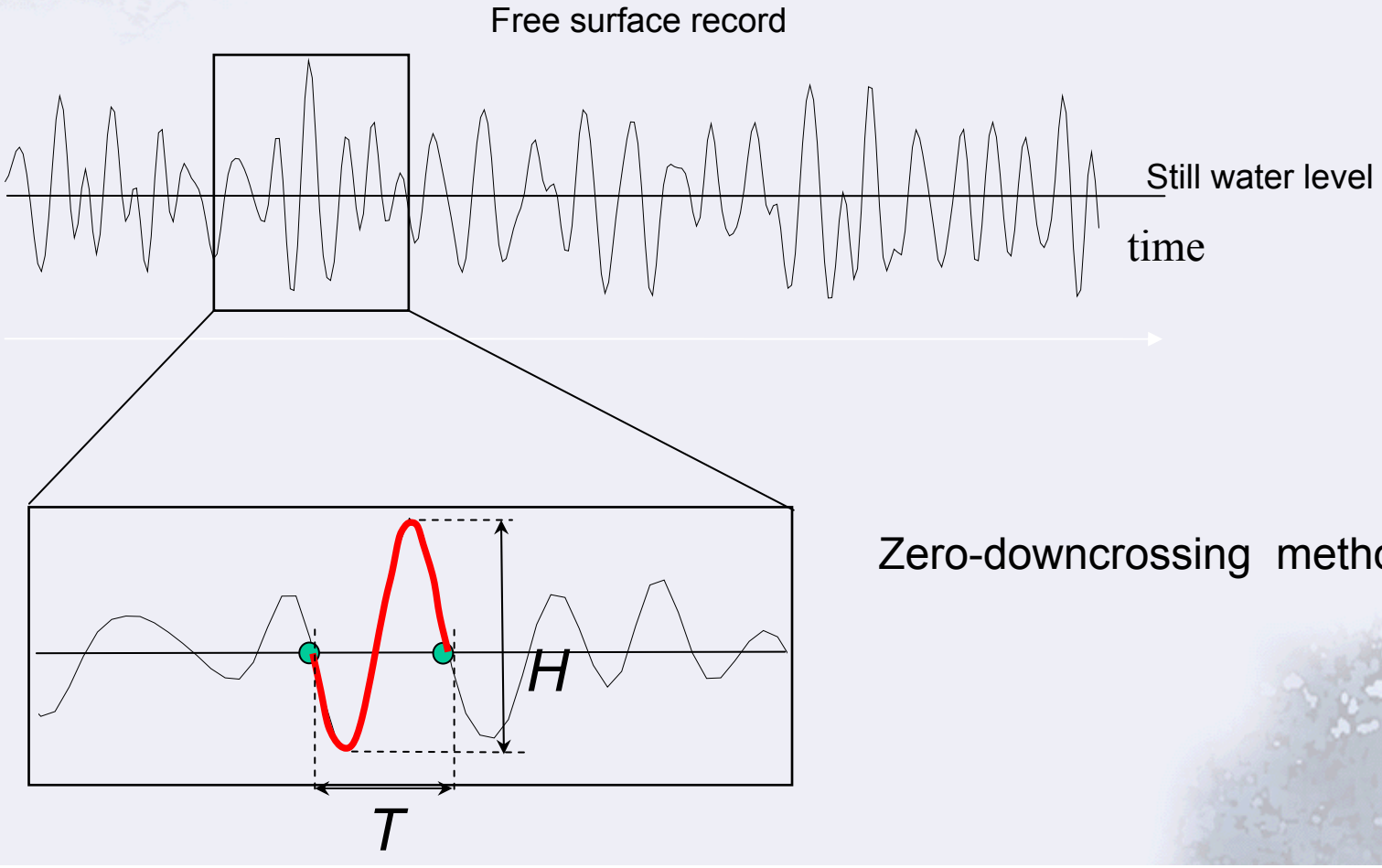
OLEAJE

- *Definición del oleaje a corto plazo*

Dominio del tiempo



Zero-downcrossing method

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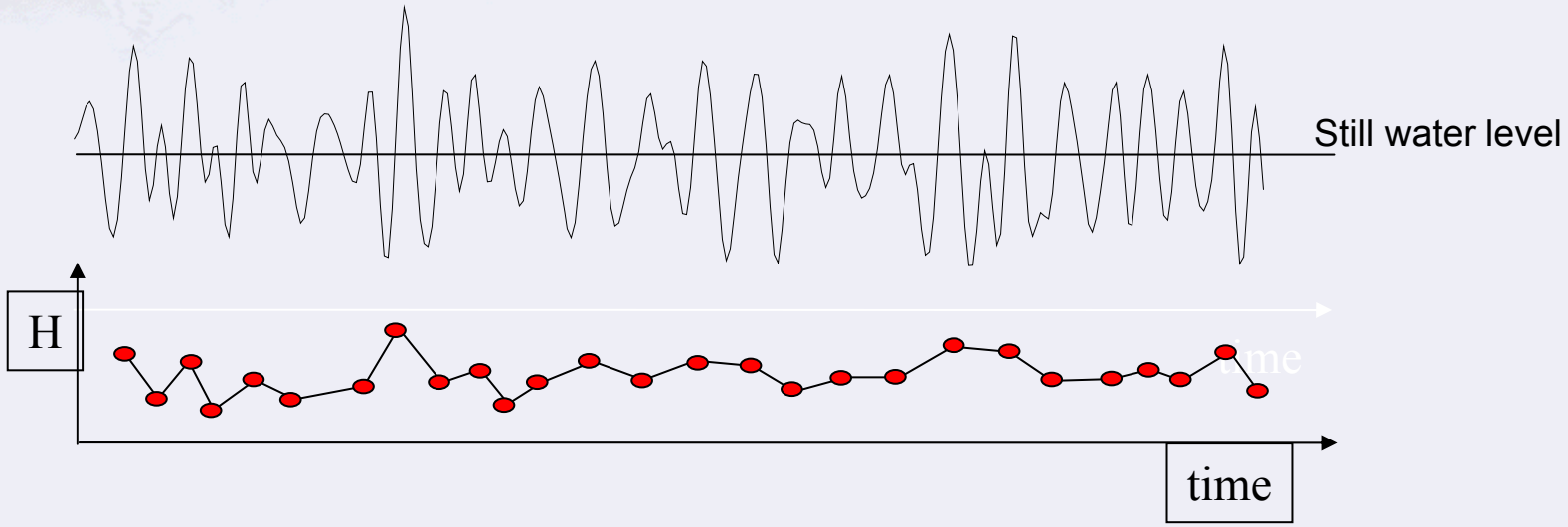
• *Definición del oleaje a corto plazo*

Dominio del tiempo



Significant wave height

$$H_s = \frac{3}{N} \sum_{i=1}^{N/3} H_i$$

Mean

$$H_m = \frac{1}{N} \sum_{i=1}^{N} H_i$$

Root-mean-squared

$$H_{rms} = \left[\frac{1}{N} \sum_{i=1}^{N} H_i^2 \right]^{1/2}$$

Maximum

$$H_{max}$$

Mean period $T_z = \frac{1}{N} \sum_{i=1}^{N} T_i$

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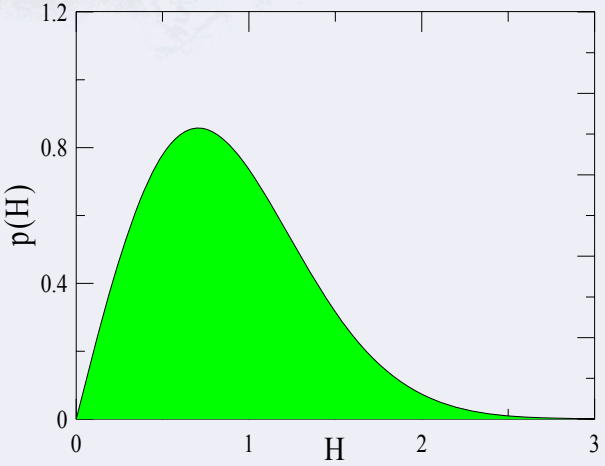
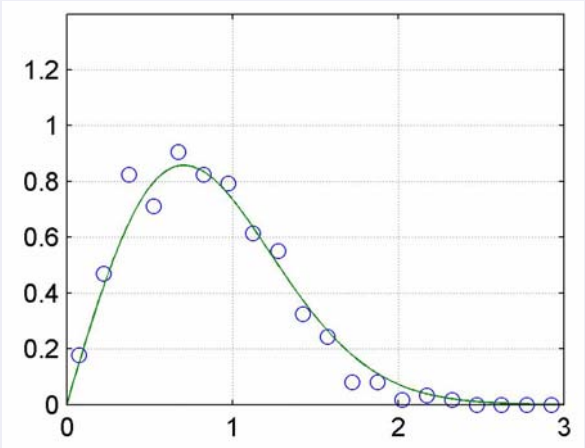
• *Definición del oleaje a corto plazo*

Dominio de la probabilidad





Model for deep water: Rayleigh

Probability density function (pdf)

$$p(H) = \frac{2H}{H_{rms}^{\ 2}} \exp\left[-\left(\frac{H}{H_{rms}}\right)^2\right]$$

Cumulative distribution function (cdf)

$$F(H) = 1 - \exp\left[-\left(\frac{H}{H_{rms}}\right)^2\right]$$

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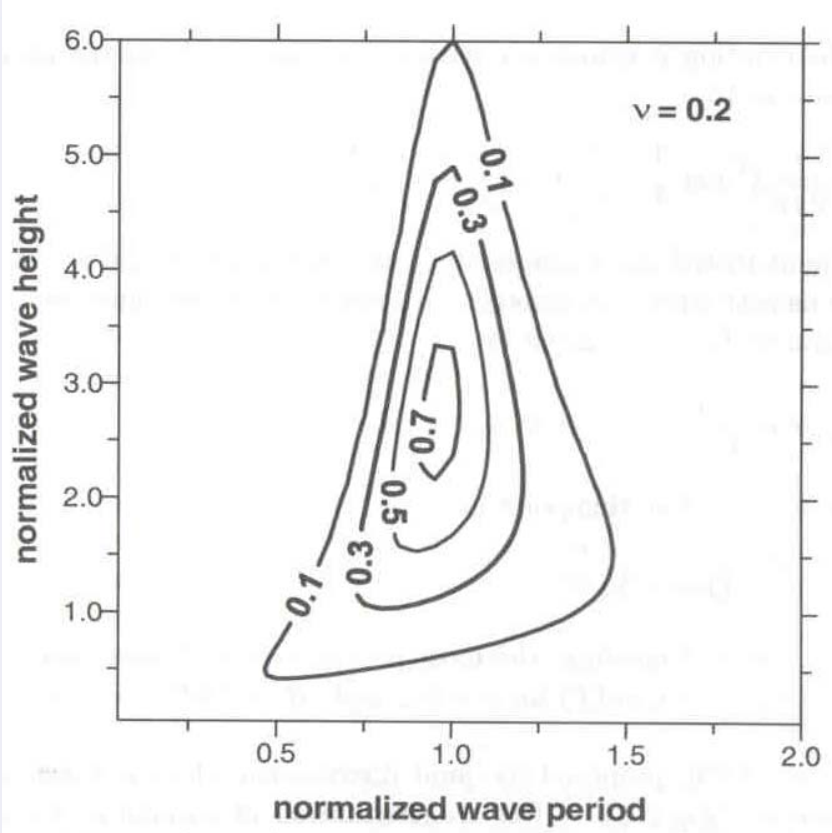
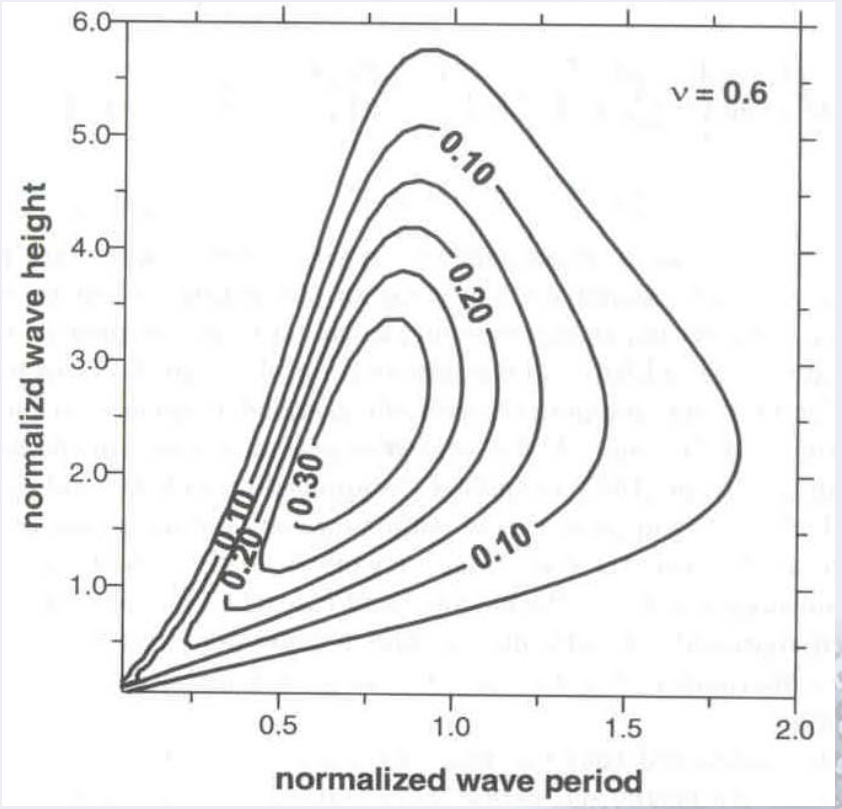
• *Definición del oleaje a corto plazo*

Dominio de la probabilidad

Joint wave height-period pdf Longuet-Higgins (1975, 1983)





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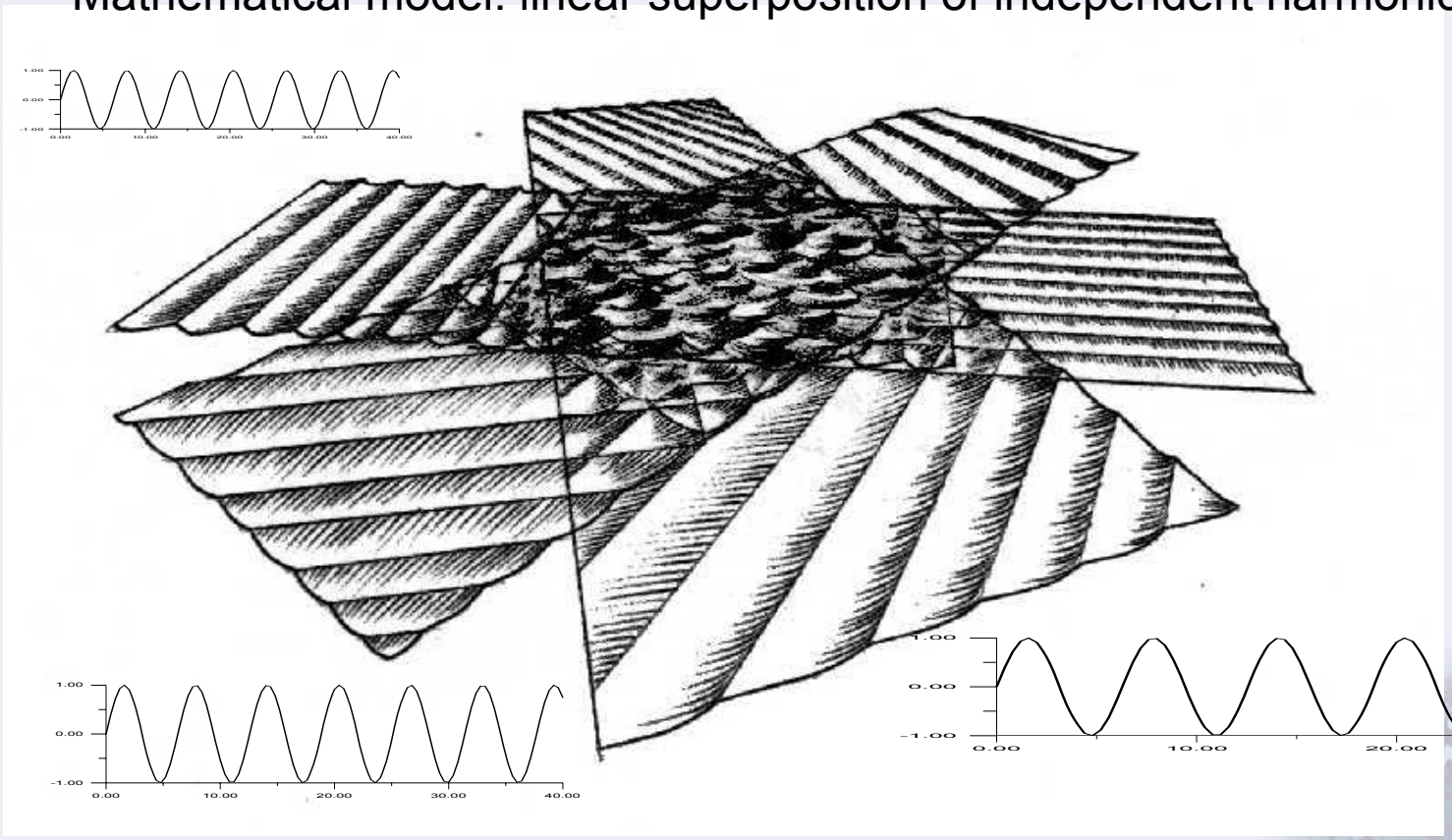
• *Definición del oleaje a corto plazo*

Dominio de la frecuencia

Mathematical model: linear superposition of independent harmonics



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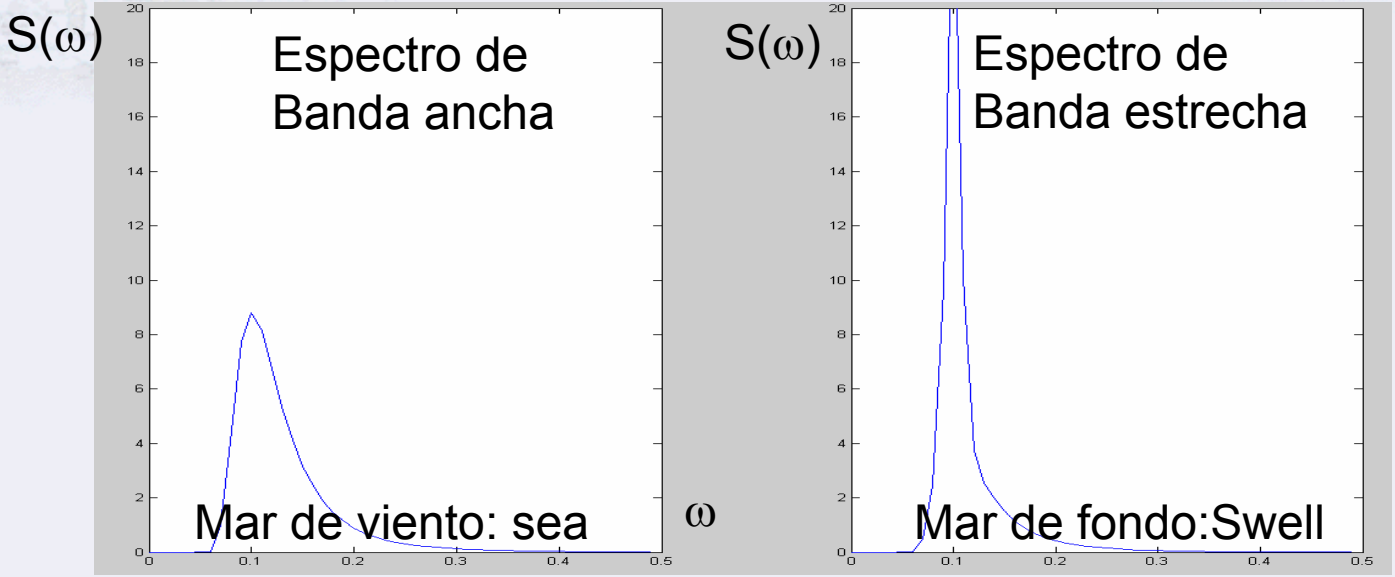
• *Definición del oleaje a corto plazo*

Dominio de la frecuencia



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• *Definición del oleaje a corto plazo*

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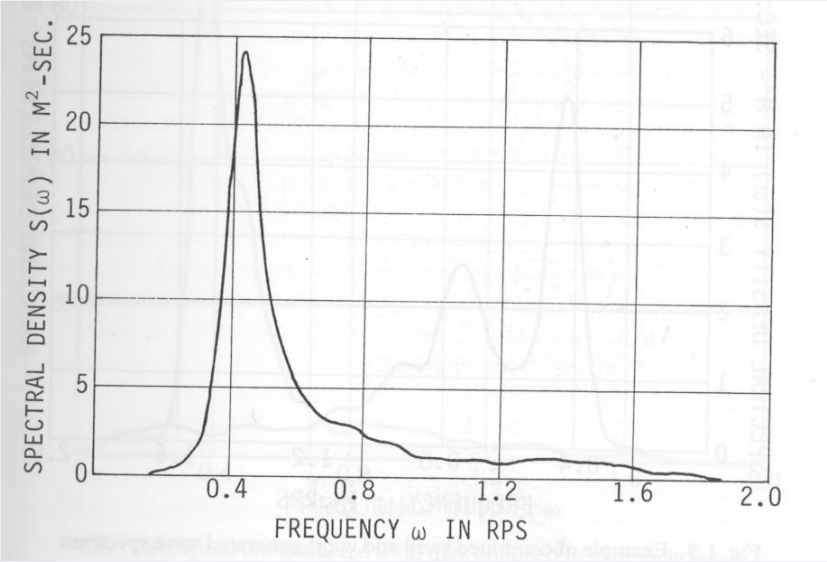

Figura I.1.5. Ejemplo de un oleaje de generación por viento (SEA). Altura de ola significante: 8.9 m.

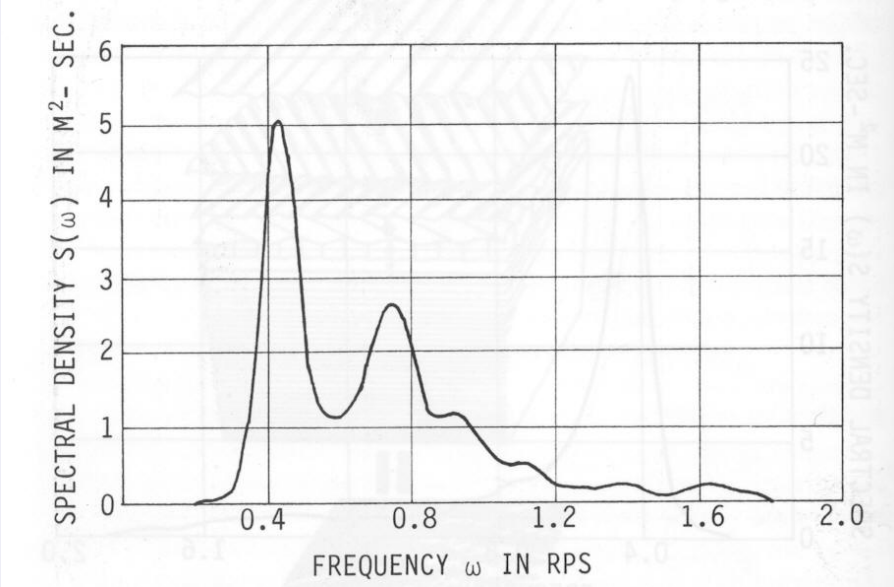

Figura I.1.6. Ejemplo del espectro de un oleaje en el que se combinan mar de viento y mar de fondo (SWELL).

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• *Definición del oleaje a corto plazo*

Dominio de la frecuencia

Dispersion Direccional

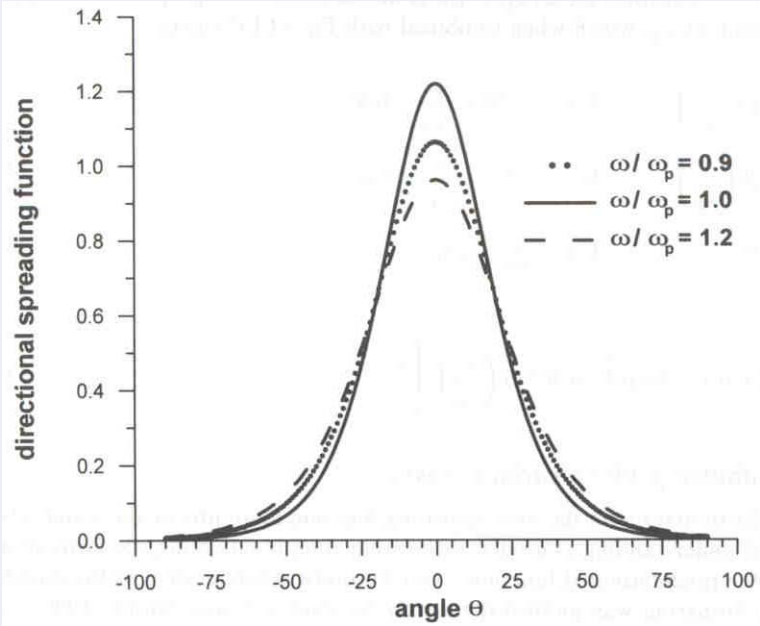

Figura I.2.9. Función de dispersión direccional hiperbólica de Donelan et al. (1985). Tomada de Massel (1996).

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• *Definición del oleaje a corto plazo*

Dominio de la frecuencia

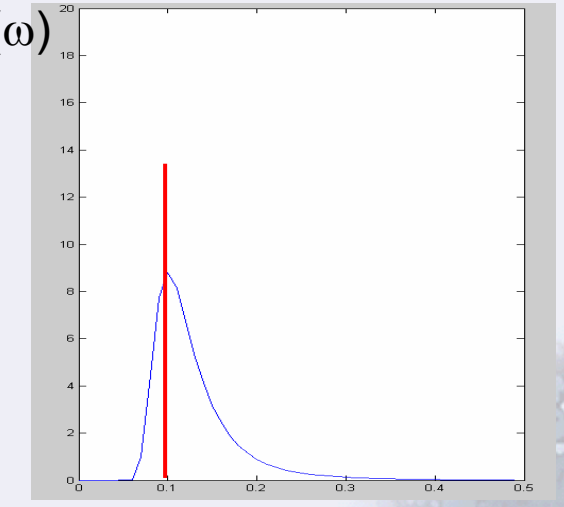
Parámetros espectrales

$$m_n = \int_0^{\infty} \omega^n S(\omega)\, d\omega \quad ; n = 0, 1, 2, ...$$

$$H_{m0} = 4.004 \sqrt{m_0}$$

$$\overline{T_z} = 2\pi \sqrt{\frac{m_0}{m_2}}$$

$$T_p = \frac{2\pi}{\omega_p}$$



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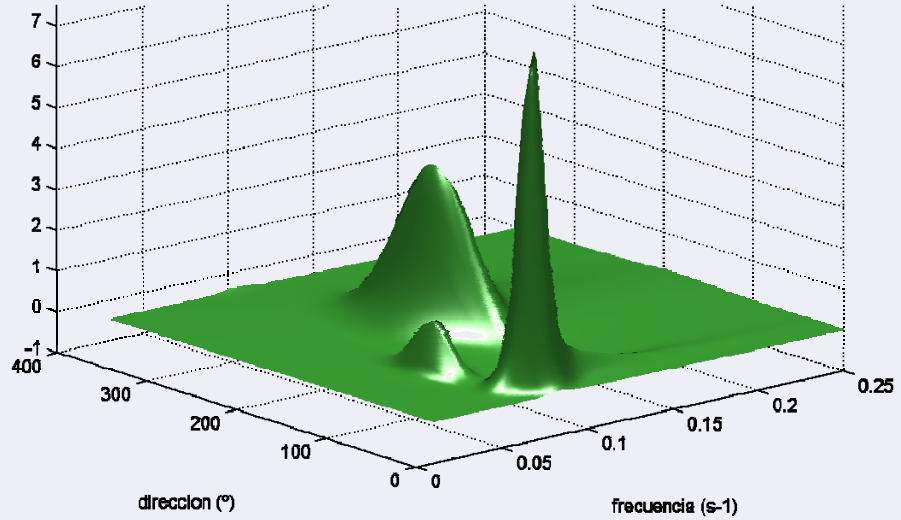
• *Definición del oleaje a corto plazo*

Dominio de la frecuencia

Espectro multidireccional



$$H_s = 4\sqrt{\iint S(f,\theta)\,df\,d\theta}$$

$$T_m = T_{0,2} = \sqrt{\frac{\iint S(f,\theta)\,df\,d\theta}{\iint f^2 S(f,\theta)\,df\,d\theta}}$$

$$\theta_m = \arctan\left[\frac{\iint \sin\theta S(f,\theta)\,df\,d\theta}{\iint \cos\theta S(f,\theta)\,df\,d\theta}\right]$$

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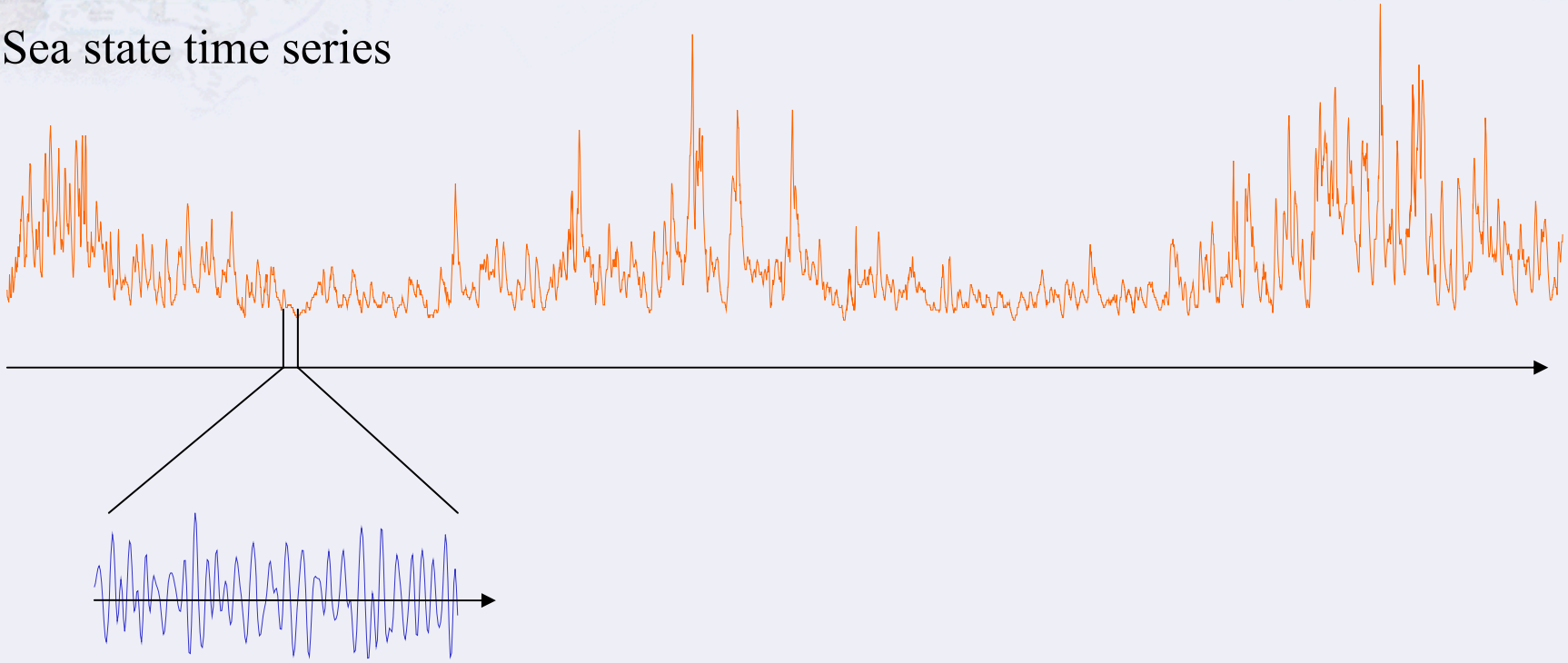
- *Clima marítimo*

Sea state time series



Statistical/spectral parameters of the sea state: Hs,Tp, θ

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BASES DE DATOS

Instrumentales (boyas escalares y direccionales, radar, mareógrafos, estaciones meteorológicas)

Datos visuales (barcos)

Datos de retroanálisis (WAM, HAMSOM)

Satélite (altimetro)

Uso de datos de oleaje y nivel del mar

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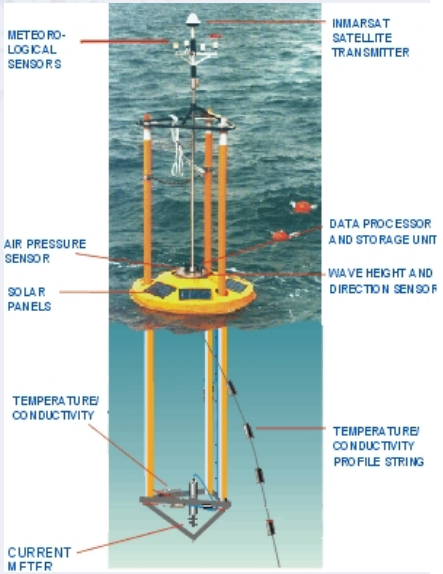
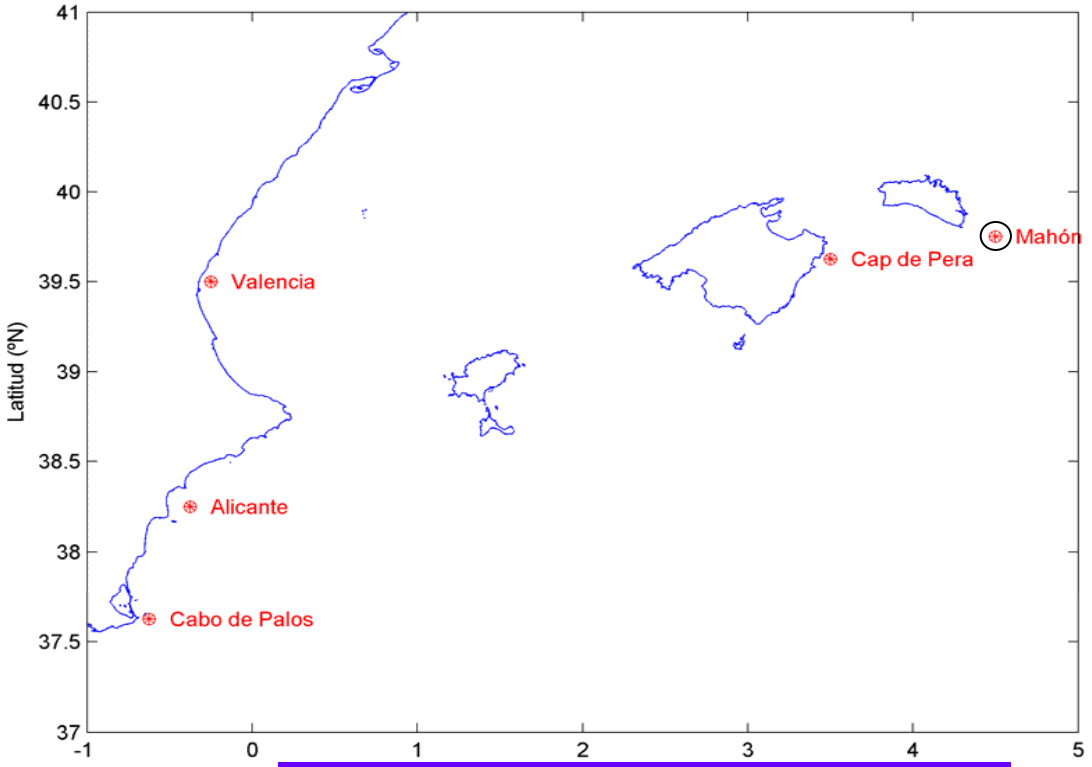
Instrumentales (boyas escalares y direccionales, radar, mareógrafos, estaciones meteorológicas)





Radar (Cabo de Peñas)

Good quantitatively
Shallow water buoys affected by propagation
Sparse in space and time, gaps
Short records (in general)

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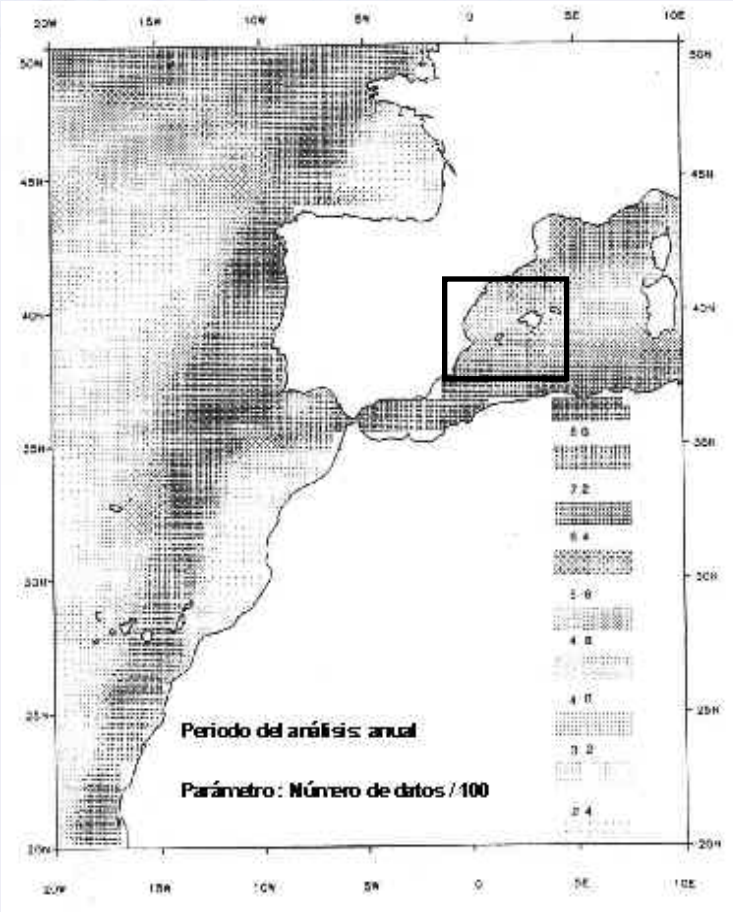
Visuales (Barcos)



British Meteorological Office (BMO).

Every singular observation:

-Longitude and latitude

-Date / hour

-Sea level pressure, Temperature

-Wind speed, wind direction

-SWELL: wave height, period, direction

-SEA: wave height, period, direction

Good qualitatively
Good directional information
Sparse in space
Long records
Extreme values are not adequate

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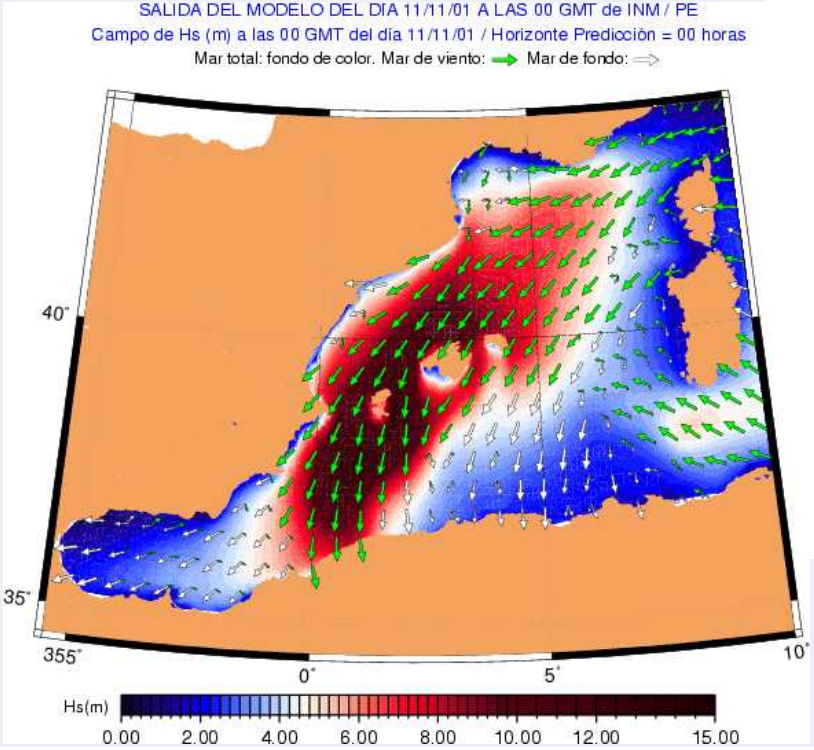
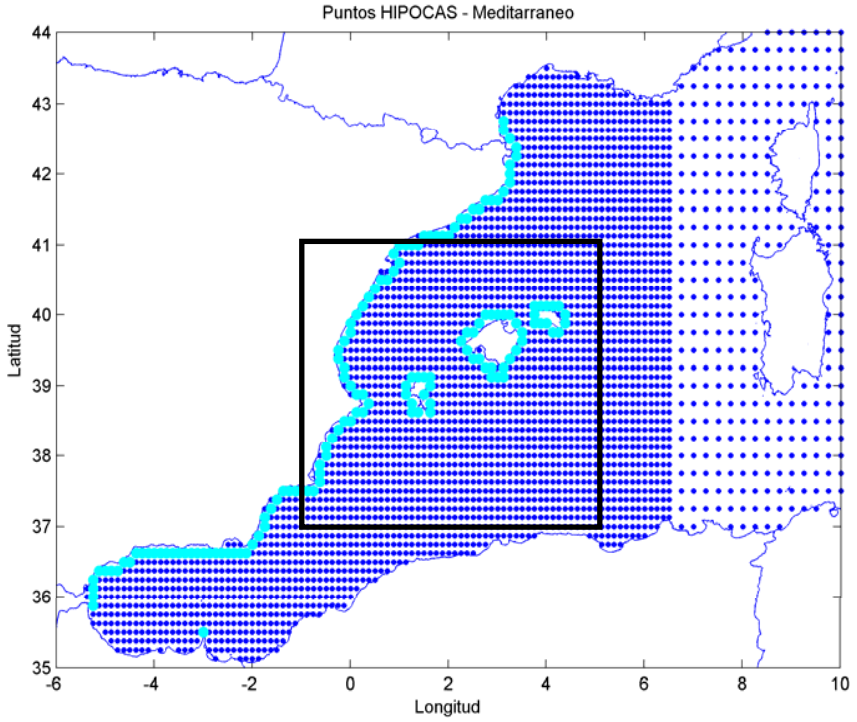
Datos de retroanálisis (WAM, HAMSOM)

Swell1 (H1,T1, Θ1) Swell2 (H2,T2, Θ2) Sea (H3,T3, Θ3)

1(3)-hour(s) continuous time series
HIPOCAS-WAM is a 44-yr reanalysis





Almost-Good quantitatively
Continuous in space and time
Long records

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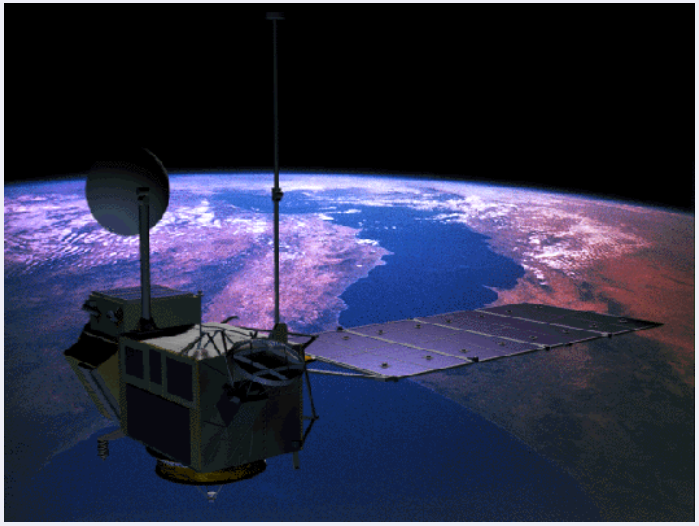
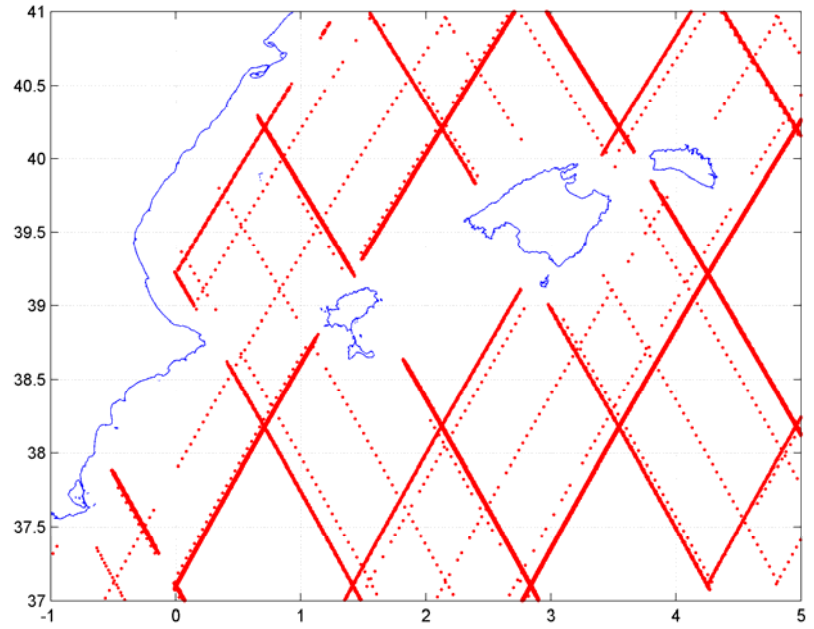
Satellite (altimeter)





H_s, T_m

recently θ_m

Good quantitatively (as buoys)
Sparse in time
Well-spatially distributed
Short records (10 years)

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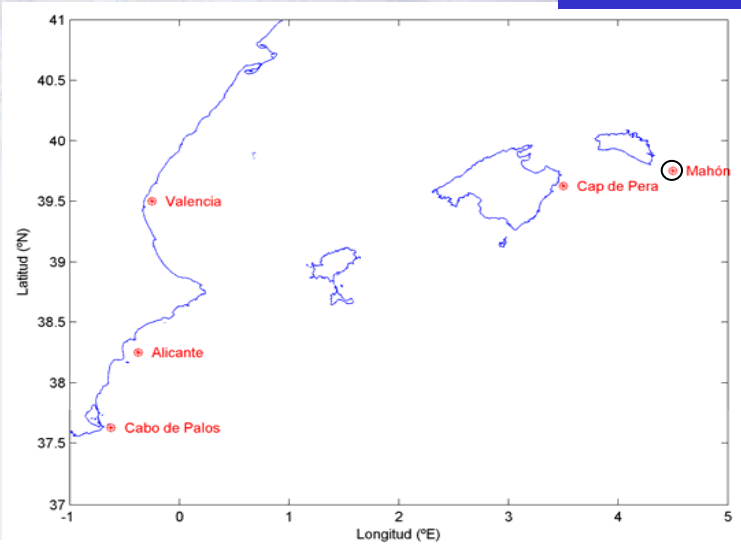
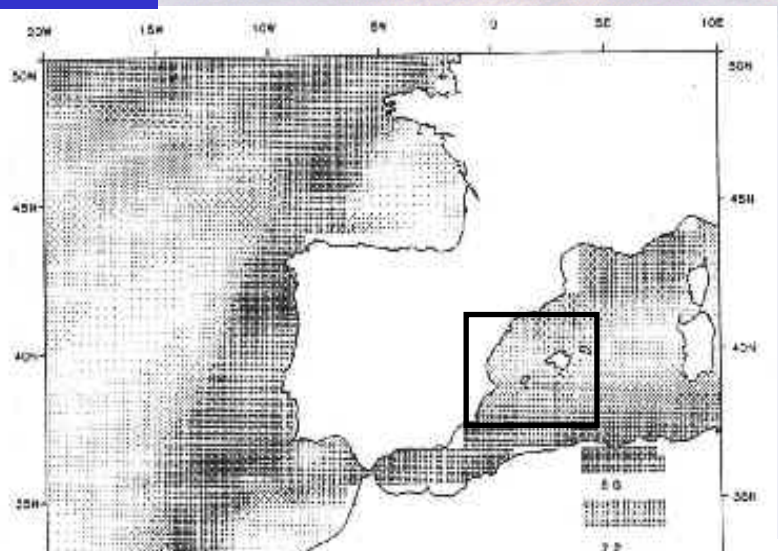
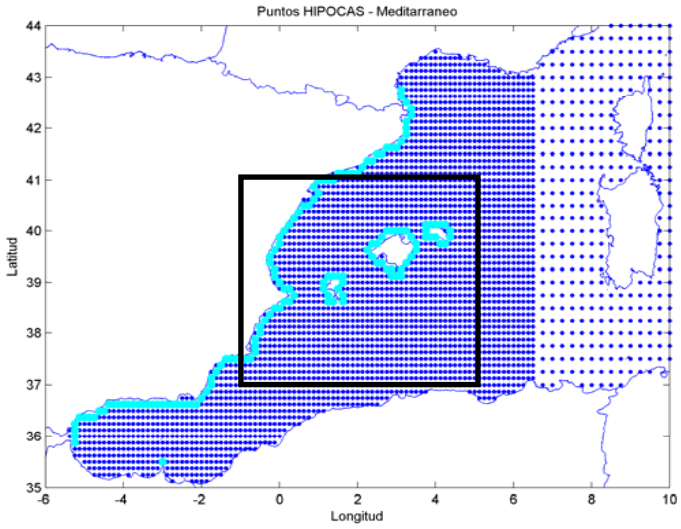
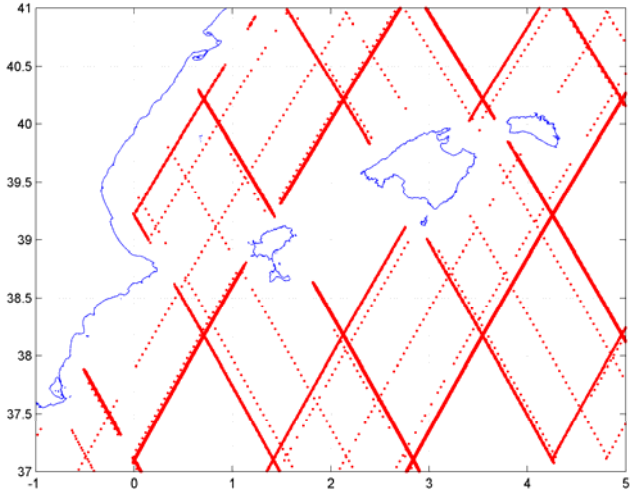
En resumen…









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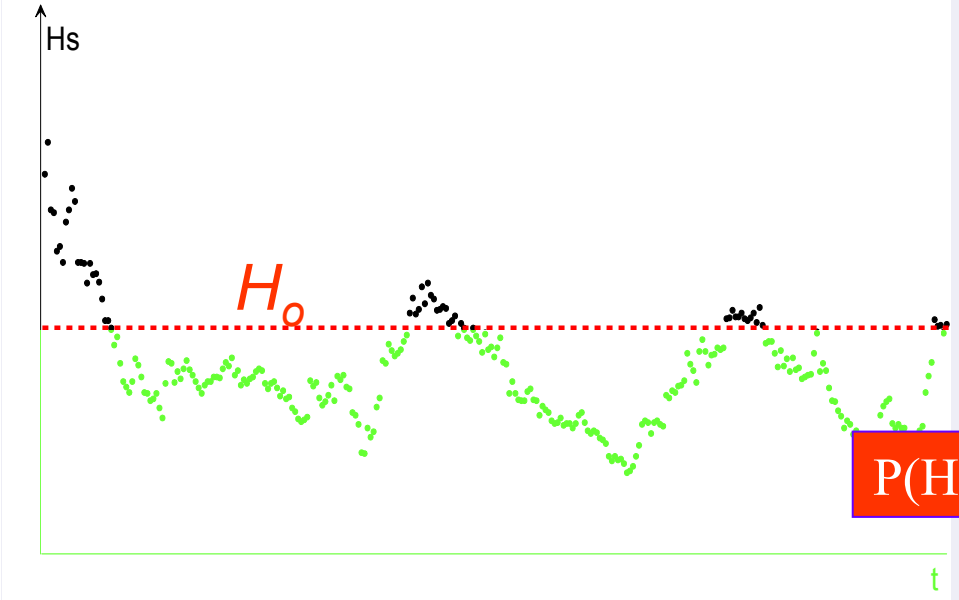
- *Wave climate*

Wave climate long-term distribution (**régimen medio**)

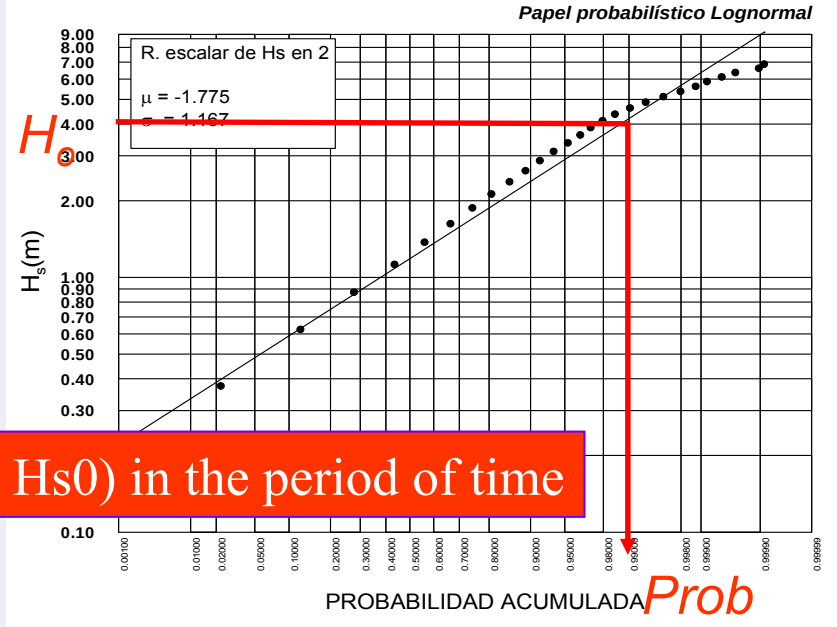
"Statistical distribution of parameters of the **sea state** in a certain period of time"

- monthly
- seasonal
- annual
- inter-annual

Period of time with quasi-stationary energy conditions (about 1 to 3 hours)



Sea state time series

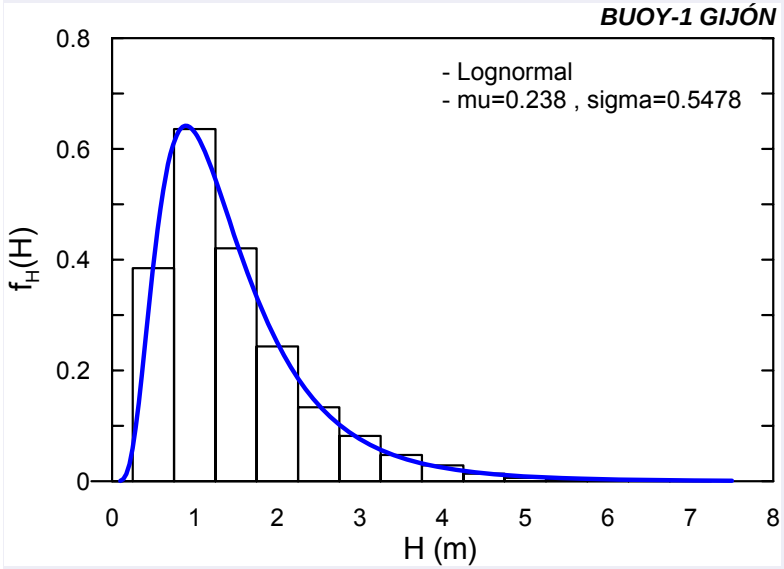


$P(Hs \leq Hs0)$ in the period of time

CDF $F_H(H)$

1. Motivation

- *Wave climate*



Mathematical model

Log-Normal $f_H(H) = \frac{1}{\sigma\sqrt{2\pi}H}\exp\left[-\frac{1}{2}\left(\frac{\log H - \mu}{\sigma}\right)^2\right]$

Weibull m $f_H(H) = \frac{\beta}{\delta}\left(\frac{H-\lambda}{\delta}\right)^{\beta-1}\exp\left[-\left(\frac{H-\lambda}{\delta}\right)^{\beta}\right]$

Other distributions frequently used:
Gumbel M, Generalized Gamma, …

Model fit

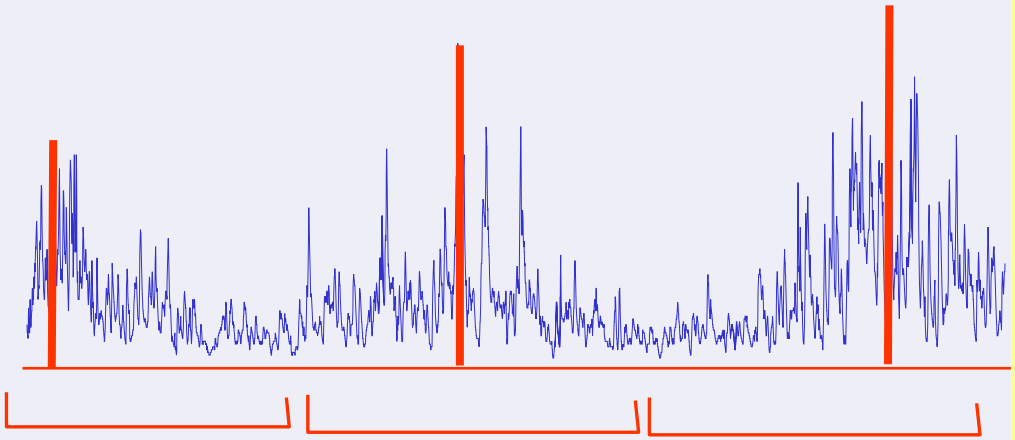
- *Graphical fitting method: Probability paper*
- *Method of moments*
- *Least square method*
- *Maximum likelihood method*

1. Motivation

- *Wave climate*

Wave climate long-term extreme value distribution (**régimen extremal**)

"Statistical distribution of the **maximum** of a parameter of the **sea state** in a certain period of time"



Analysis of extreme value series

Annual maxima method

Peak Over Threshold (POT) method

Annual R-largest method

1. Motivation

R.O.M.

(Recomendaciones para Obras Marítimas, Puertos del Estado 2001)

"Recommendations for maritime and harbor works in Spain

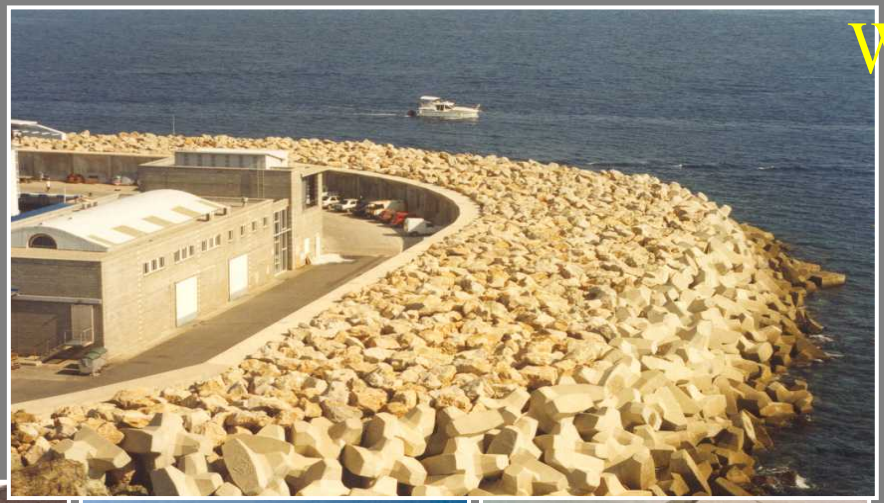
Chapter 2: Project general criteria

"All **maritime work** is constructed to comply, during an interval of time, with specific functions, according to certain requirements of **reliability**, **functionability** and **operability**"

reliability	Extreme conditions	Long-term extreme value distribution
functionability and **operability**	Mean conditions	Long-term distribution

- *Wave climate*

reliability Extreme conditions Long-term extreme value distribution



$W = f(H,T,\Theta)$

$Ru = f(H,T,\Theta)$

1. Motivation

- *Wave climate*

functionability and **operability**

Mean conditions

Sediment transport = f(H,T,Θ)

Long-term distribution

Agitation = f(H,T,Θ)

Operativity depends also on
Duration of excedance of H

Equilibrium planform depends on
energy mean flux vector

1. Motivation

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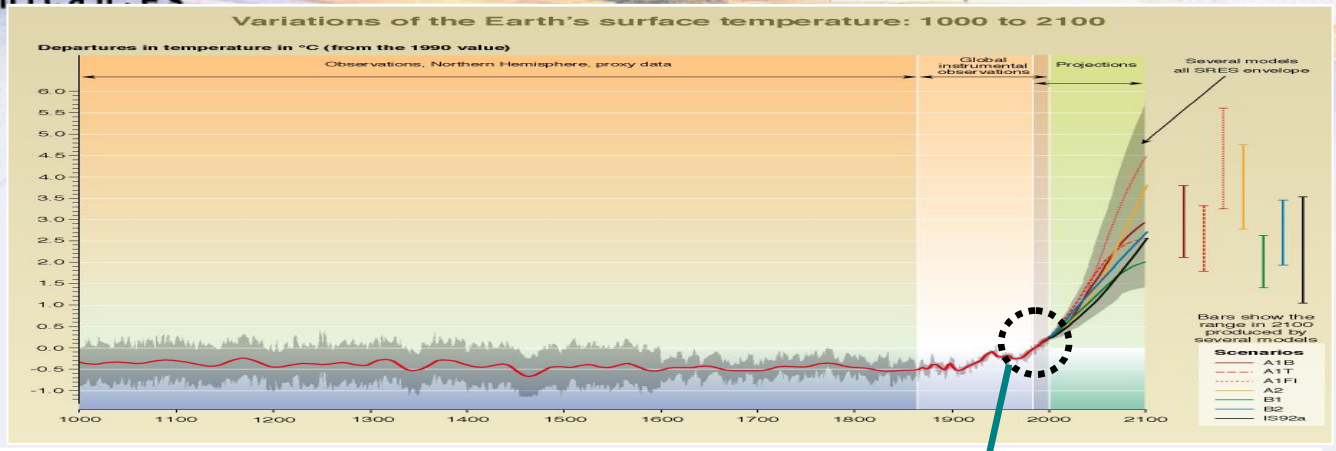

We are aware of recent trends

Is wave climate being affected by climate change ?

1. Motivation

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IPCC
Intergouvernamental Panel On Climate Change

“ A small increment of the SST can induce changes in the frequency and intensity of the extreme events “

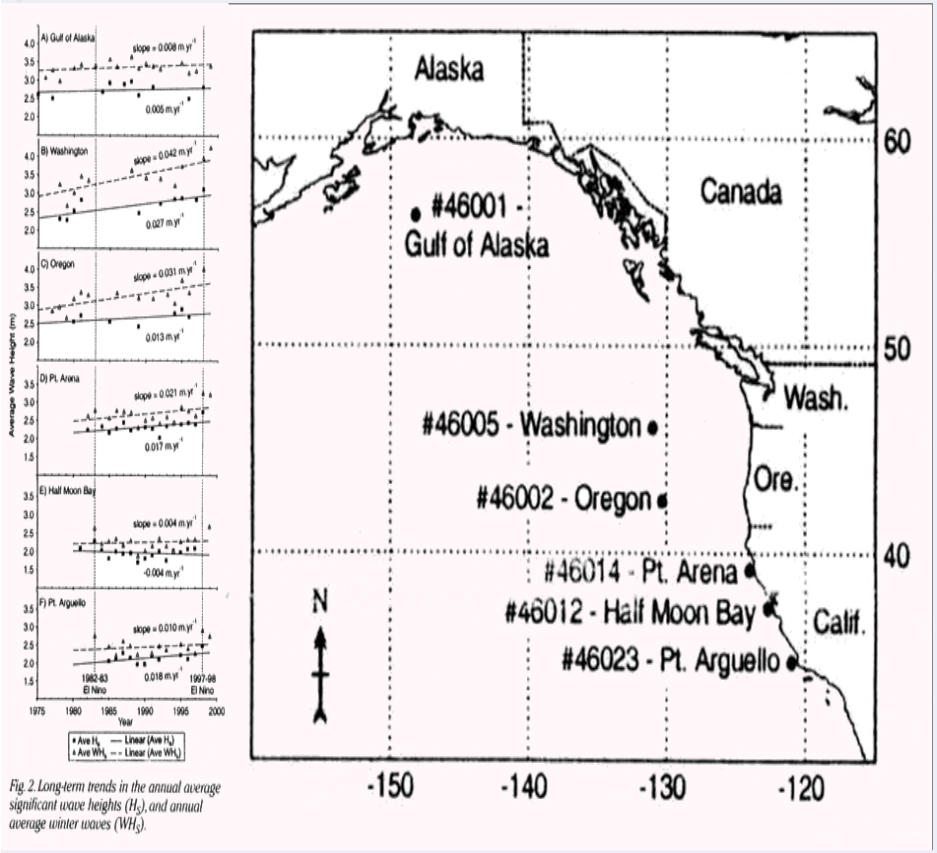
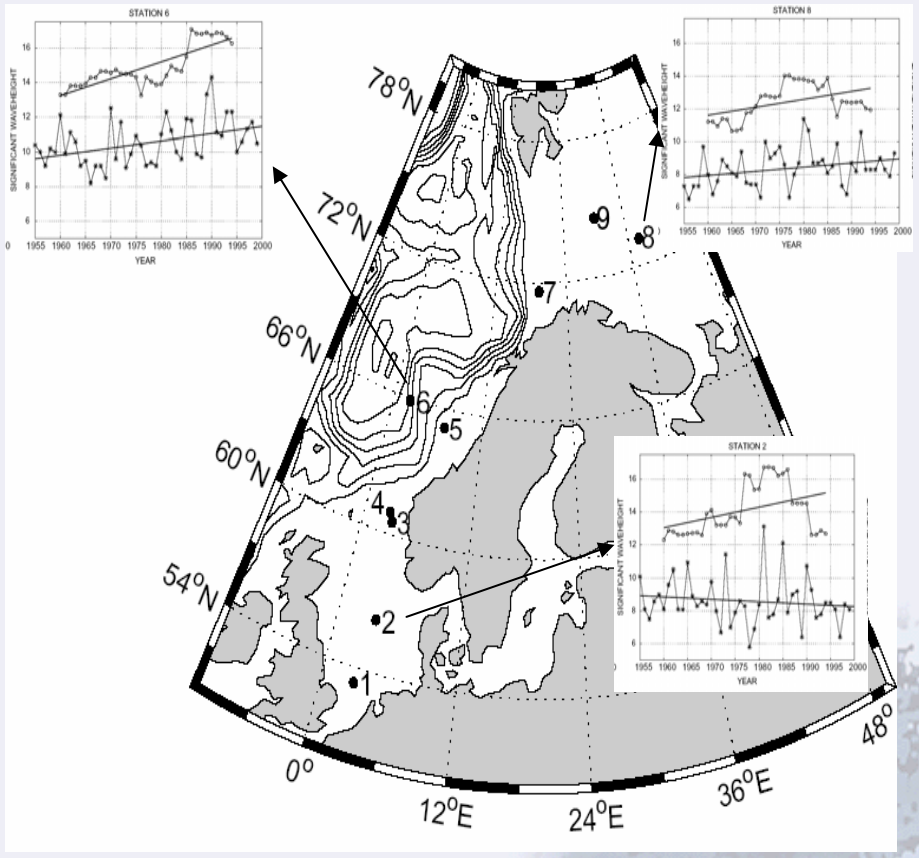


Fig 2. Long-term trends in the annual average significant wave heights (H_S), and annual average winter waves (WH_S).



1. Motivation

Are…

… being affected by wave climate changes ?

We are interested in trends in…

- mean sea level
- long-term distribution of significant wave height (SWH)
- direction of mean energy flux
- intensity and frequency of extreme events (SWH, surge, Wind)
- extreme sea levels and flooding risk

1. Motivation

TOOLS: historical data sets

Instrumental
- tide gauges (1900 – 2000)
- buoys (1975 – 2000)

Numerically obtained (1950 – 2000)
- Wave reanalysis
- Sea level reanalysis

- Good quantitavely
- Sparse in time and space
- Short-term records

- Good qualitavely
- Well-defined spatially
- Long-term records

OBJECTIVES

- **To perform spatial calibration of reanalysis models**

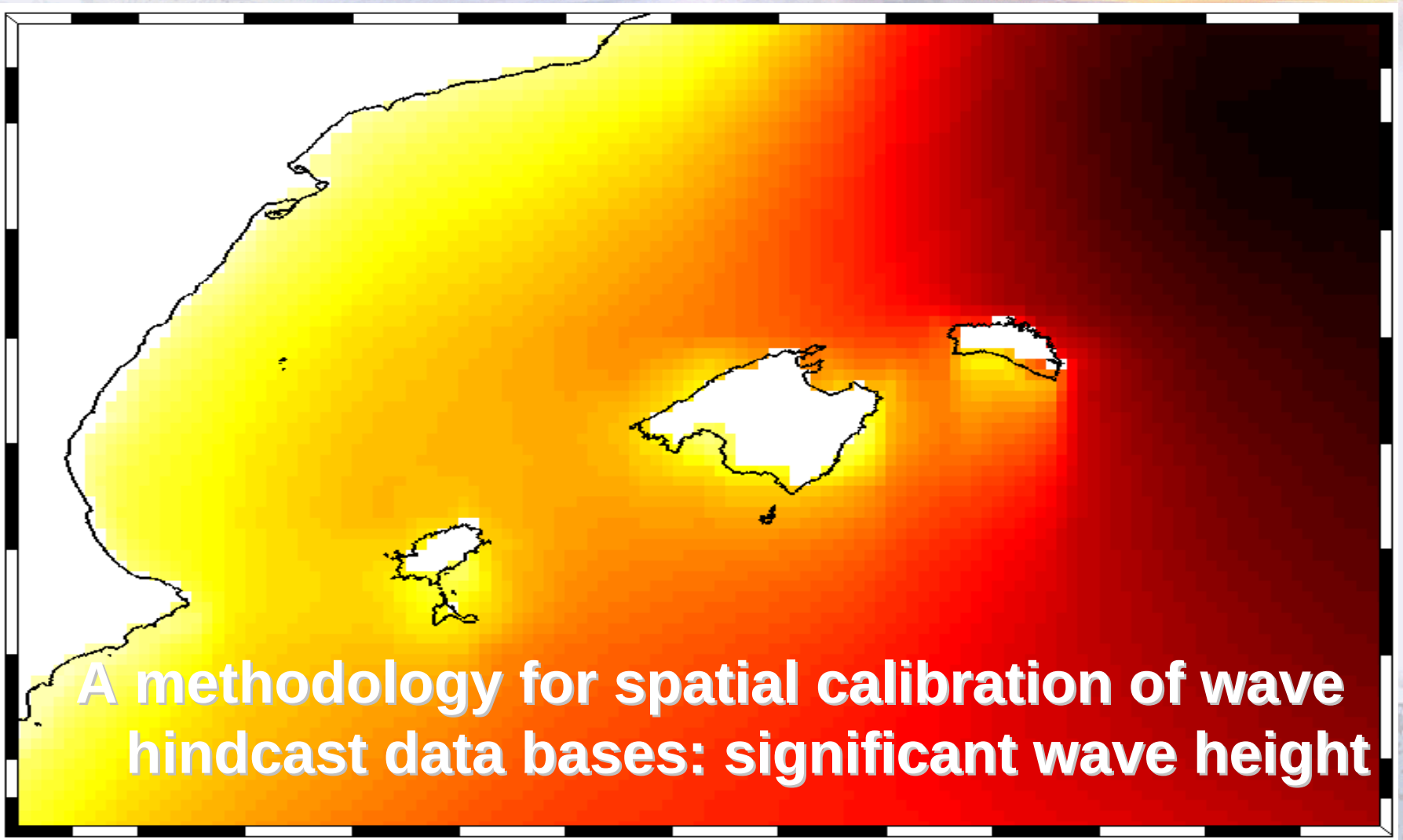
- **To develop statistical models to estimate recent trends in wave climate parameters**

Outline

1. Motivation
2. Spatial calibration
3. Time scales of wave climate variability
4. Trends in long-term distributions
    1. Scalar variables
    2. Directional variables
5. Trends in long-term extreme value distributions
6. Effects of climate change on the spanish coast

CALIBRATION

Reanalysis data. Spatial



A methodology for spatial calibration of wave hindcast data bases: significant wave height

1. Introduction
2. Calibration
   1. Methodology
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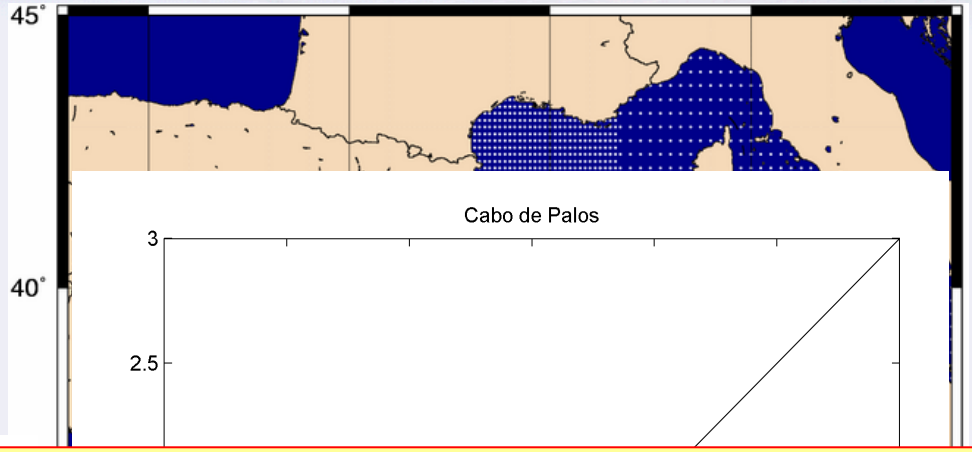
5. Conclusions

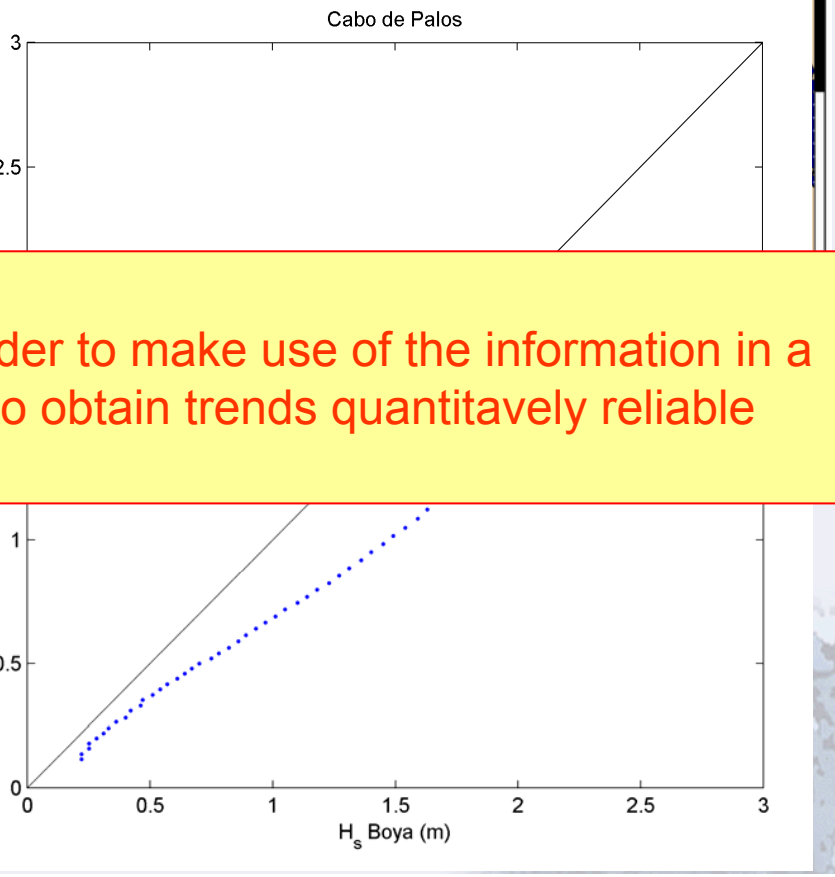
CALIBRATION

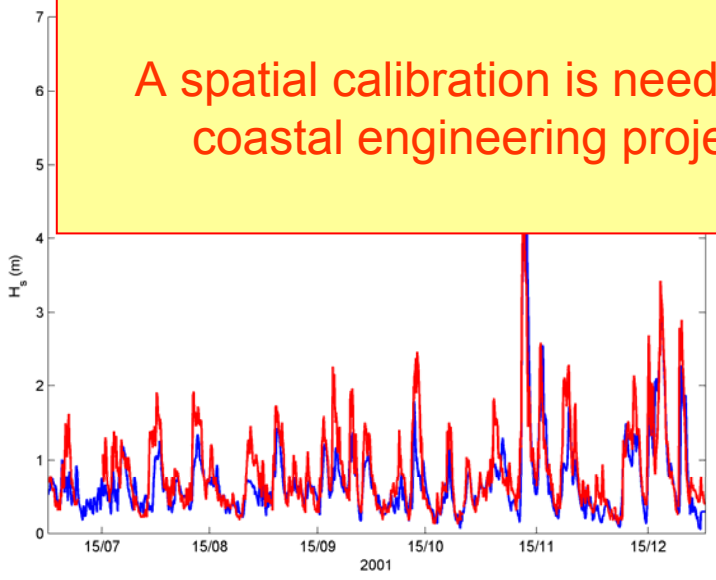
Reanalysis data. Spatial

Project HIPOCAS (***HI**ndcast of dynamic **P**rocesses of the **O**cean and **C**oastal **A**rea**S** of Europe)*

- Puertos del Estado
- 44-year reanalysis (1958-2001)
- Hourly time resolution
- Spatial resolution 0.125º



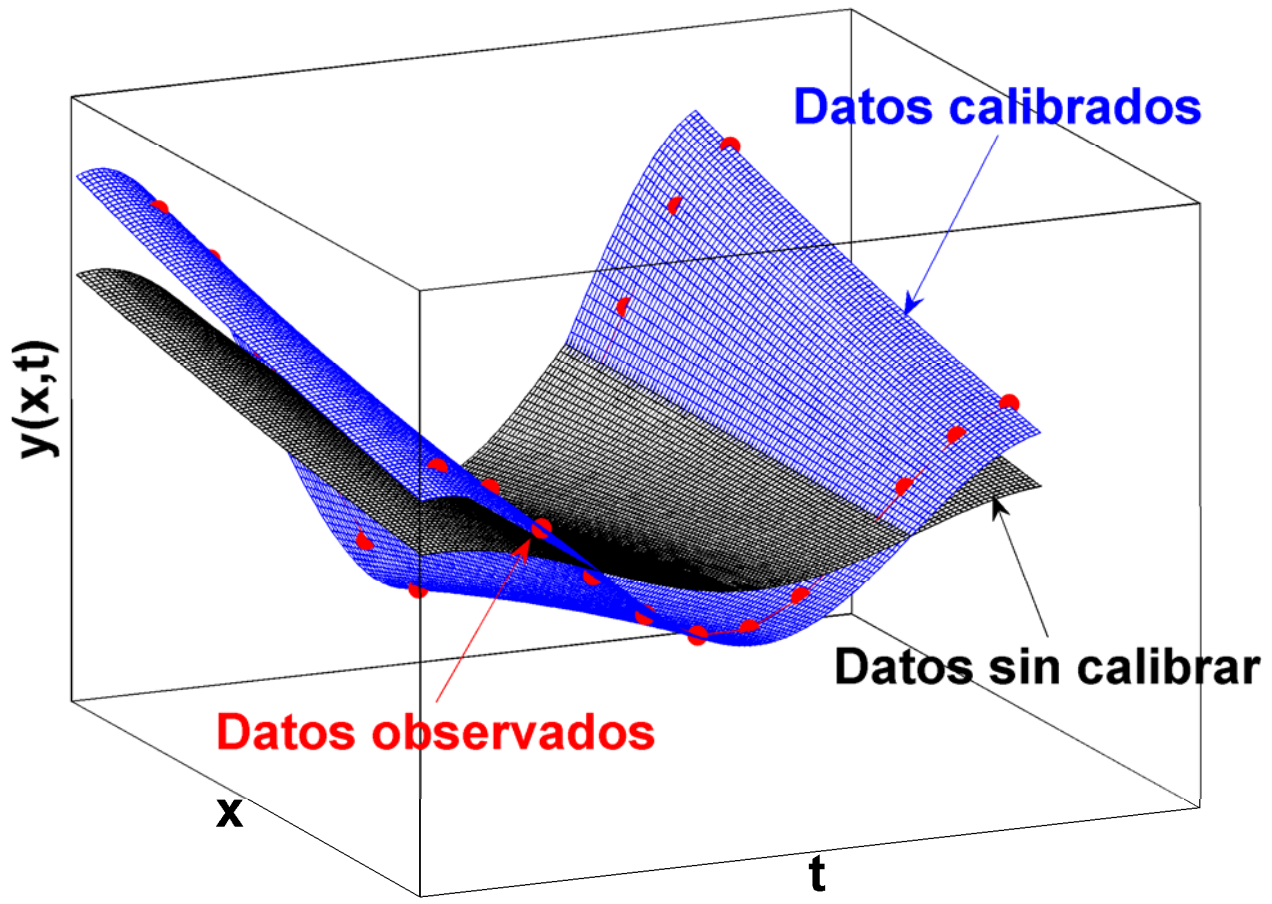




A spatial calibration is needed in order to make use of the information in a coastal engineering project and to obtain trends quantitavely reliable

CALIBRATION

Reanalysis data. Spatial



CALIBRATION

Reanalysis data. Spatial

1. Introduction

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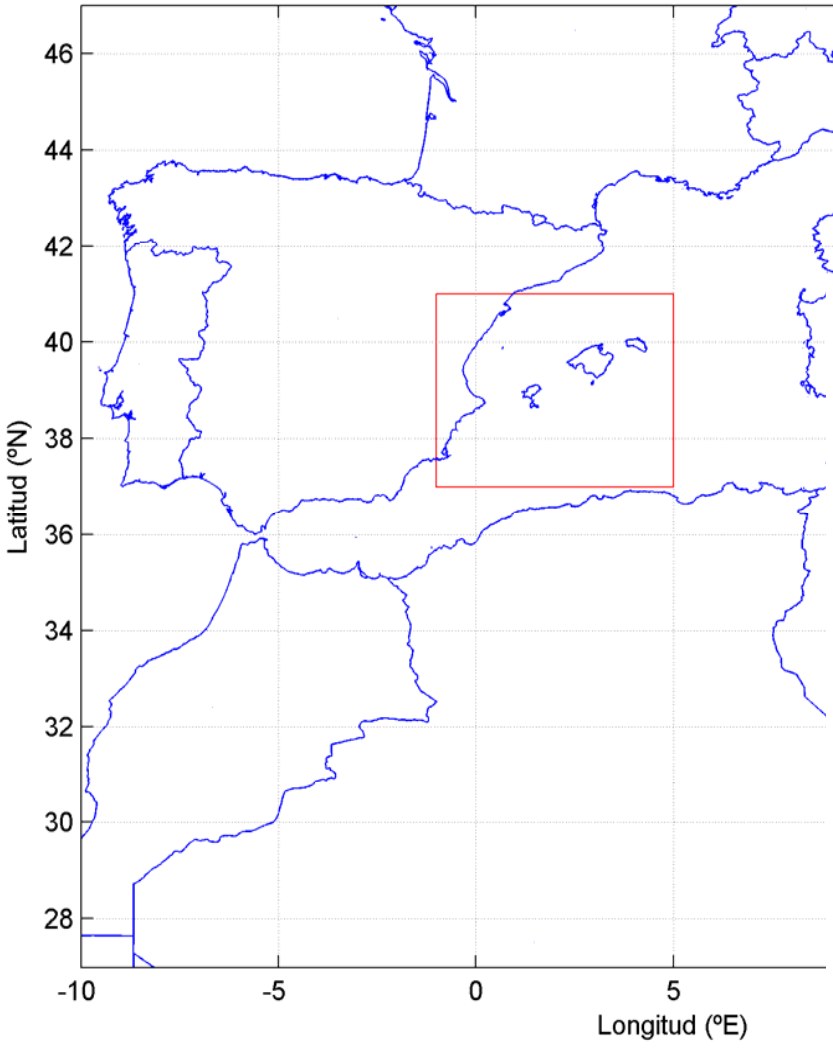
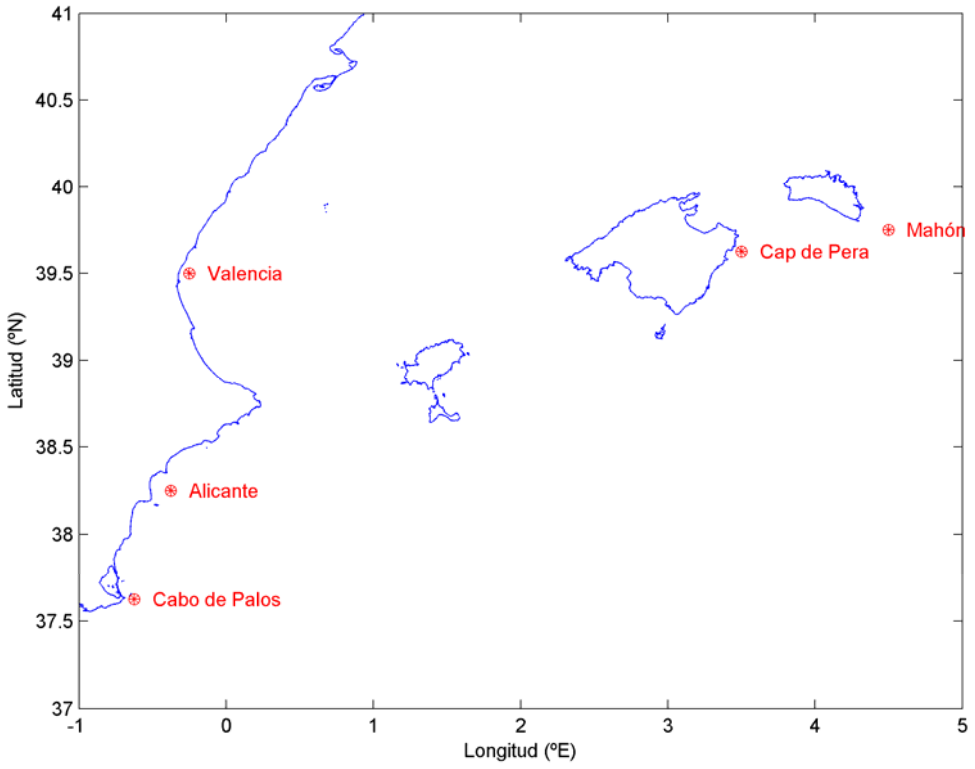
CALIBRATION

Reanalysis data. Spatial

Methodology applied to a specific location in the Western Mediterranean sea



- H_S=*SWH*
- (37ºN-41ºN, 1ºW-5ºE)



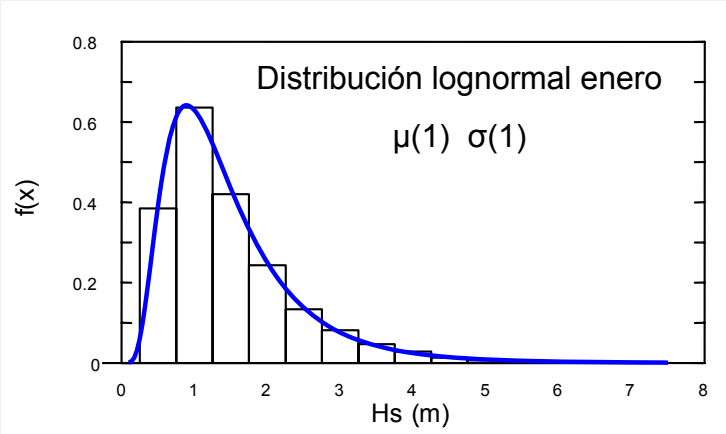
Aggregation of the original SWH time series using monthly long-term distributions

For every point:

	Original time series		Monthly aggregation
Time unit:	t 385440 hours	$\longrightarrow$	τ 12 months
Parameters	H_s	$\longrightarrow$	$\mu\ \sigma$ Lognormal
	$H_s(t)$	$\longrightarrow$	$\mu(\tau)\ \sigma(\tau)$

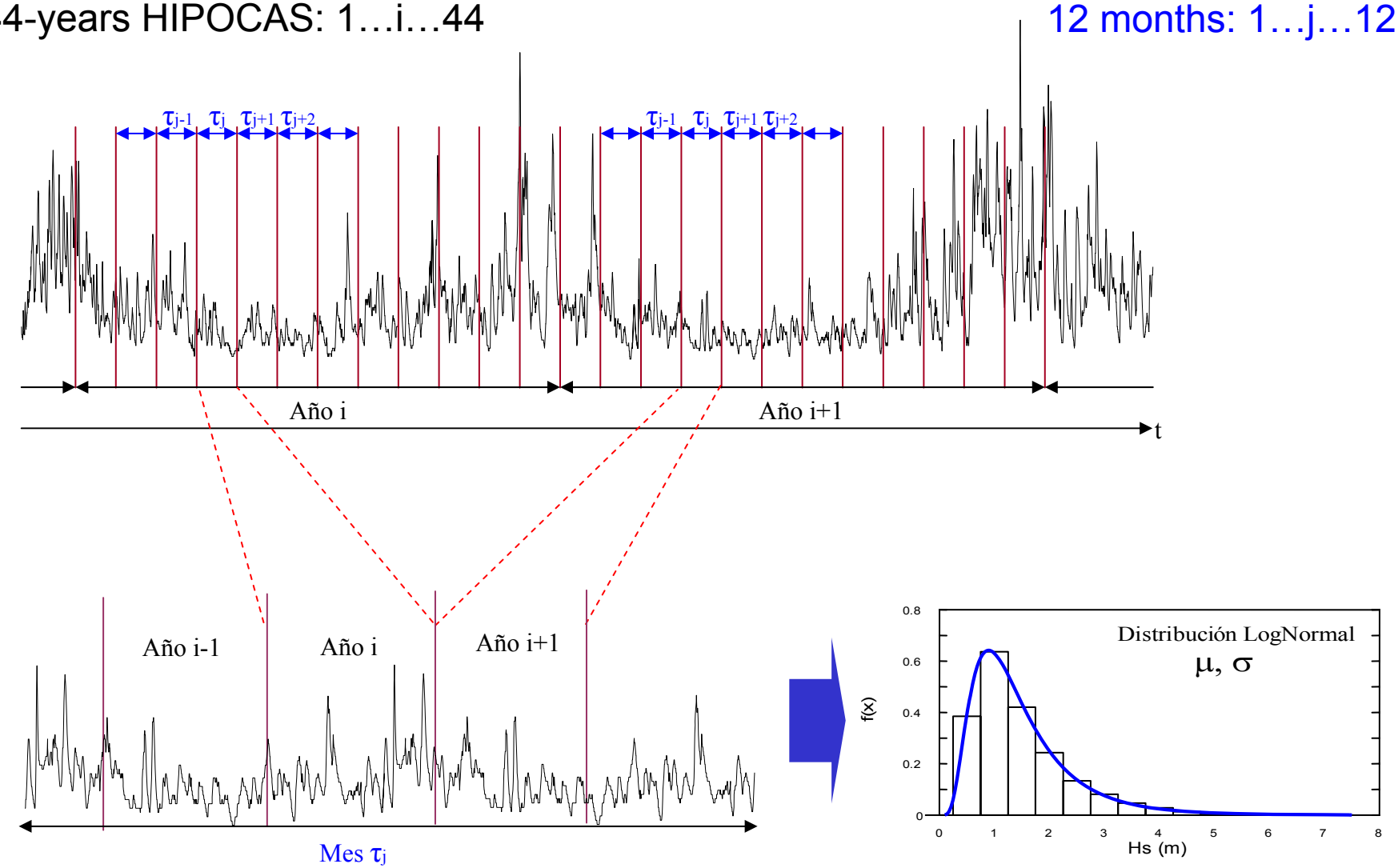
New time unit: $\tau_1 \ldots \tau_j \ldots \tau_{12}$

We loose instanteneous information



44-years HIPOCAS: 1…i…44

12 months: 1…j…12



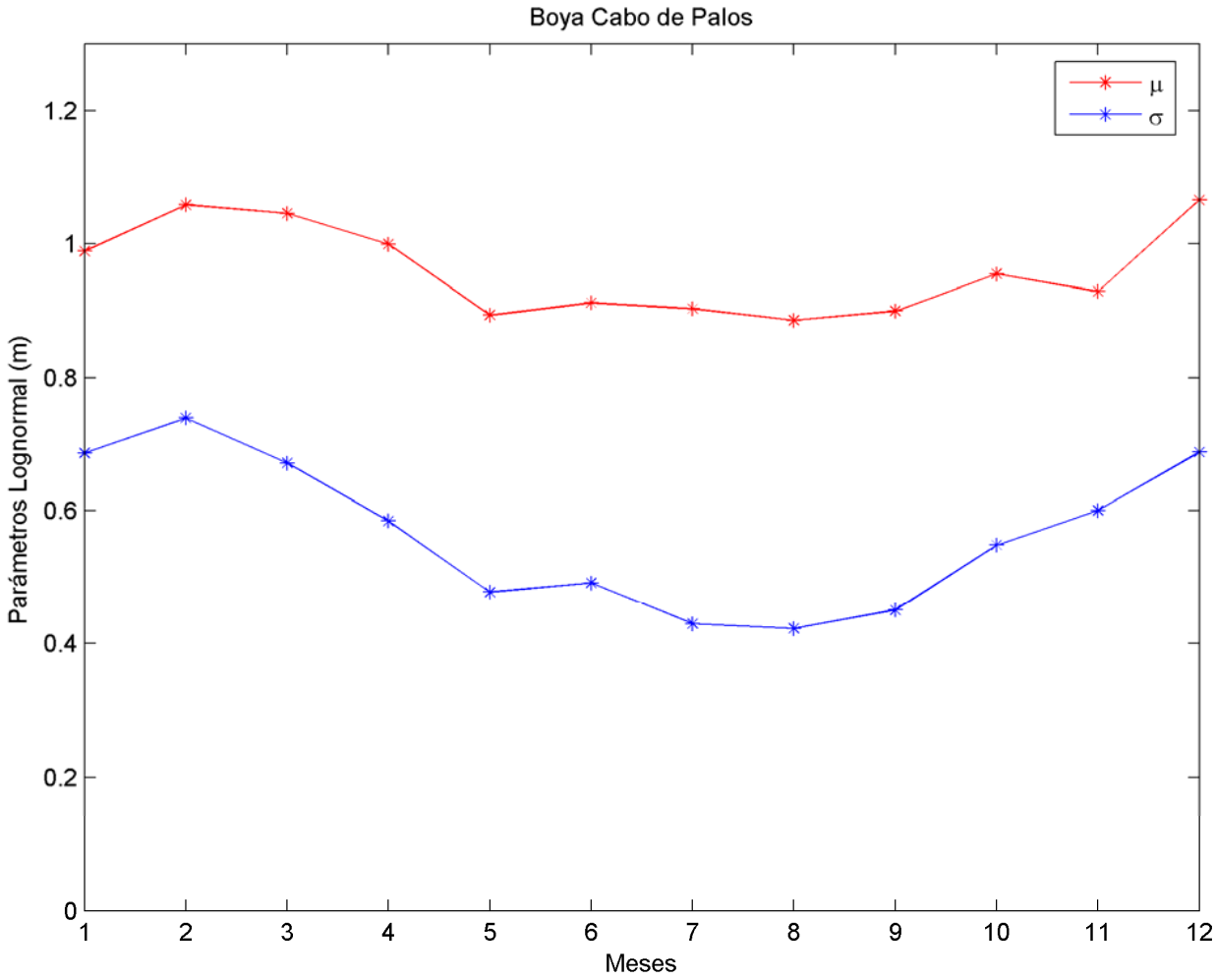
Aggregation of the original SWH time series using monthly long-term distributions

CALIBRATION

Reanalysis data. Spatial

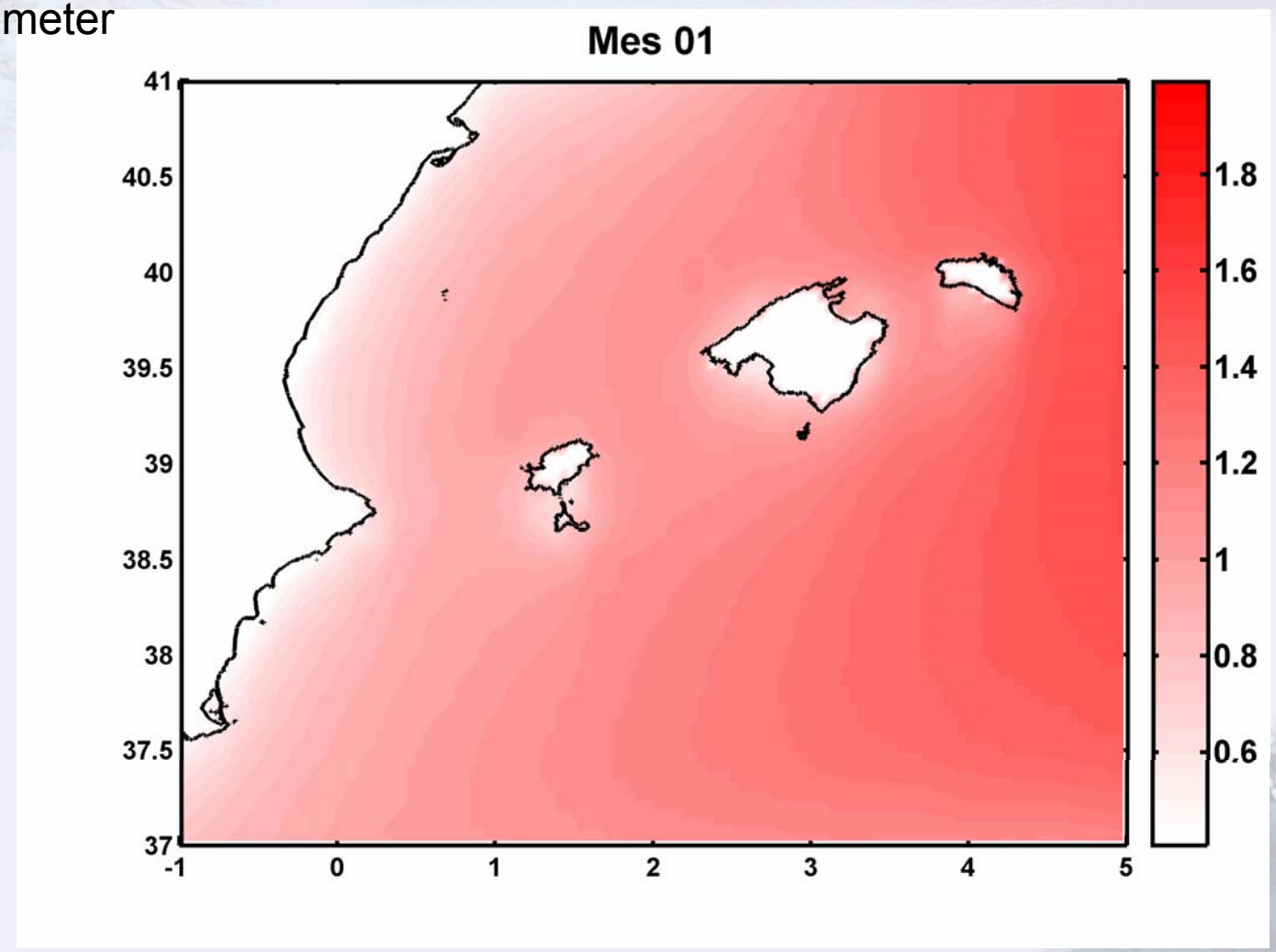
Monthly long-term distribution

(in a buoy)



HIPOCAS monthly long-term distribution: location parameter

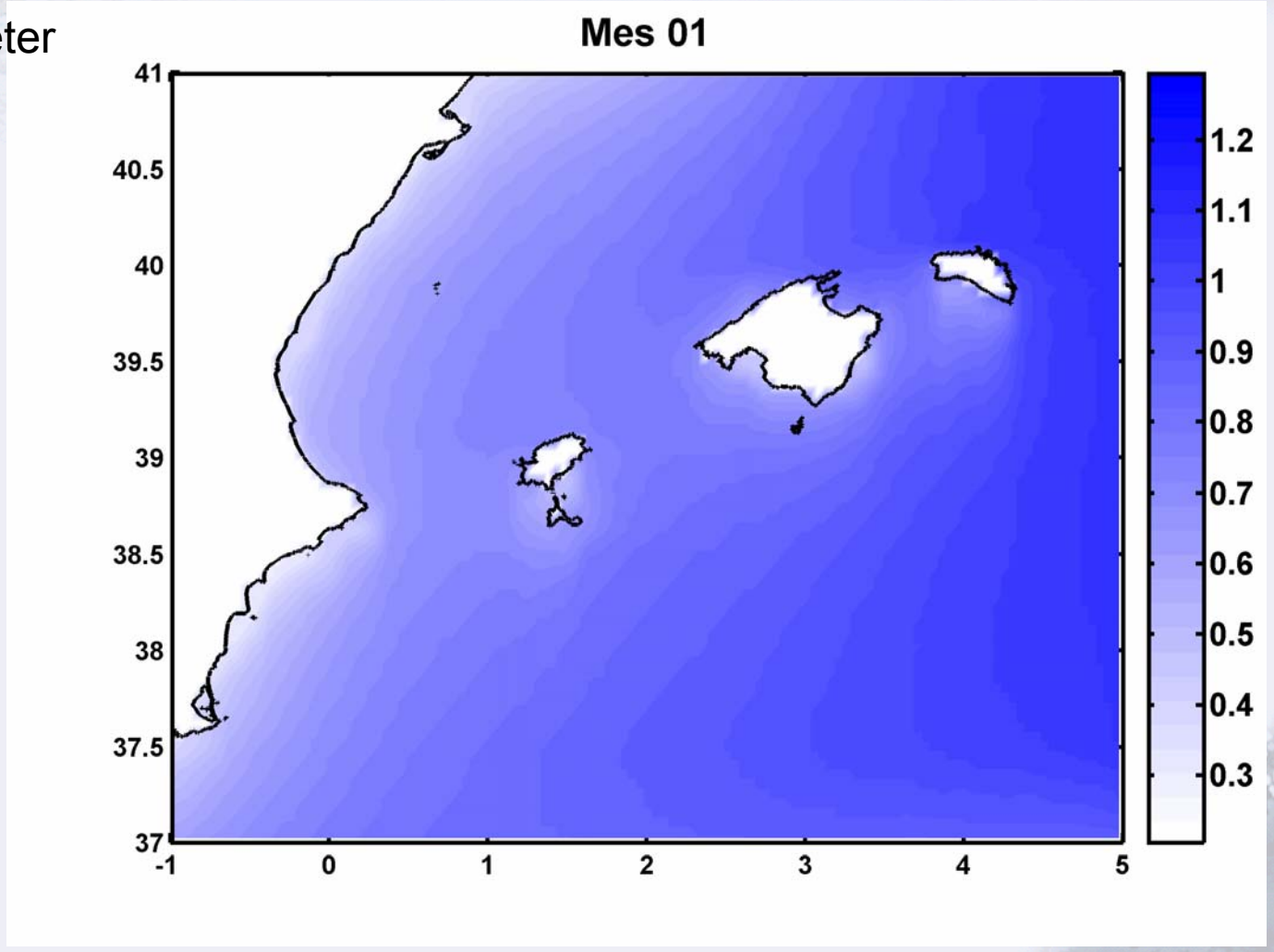
$$\mu(\mathbf{x},\tau)$$



HIPOCAS monthly long-term distribution:

scale parameter

$\sigma(\mathbf{x},\tau)$



CALIBRATION

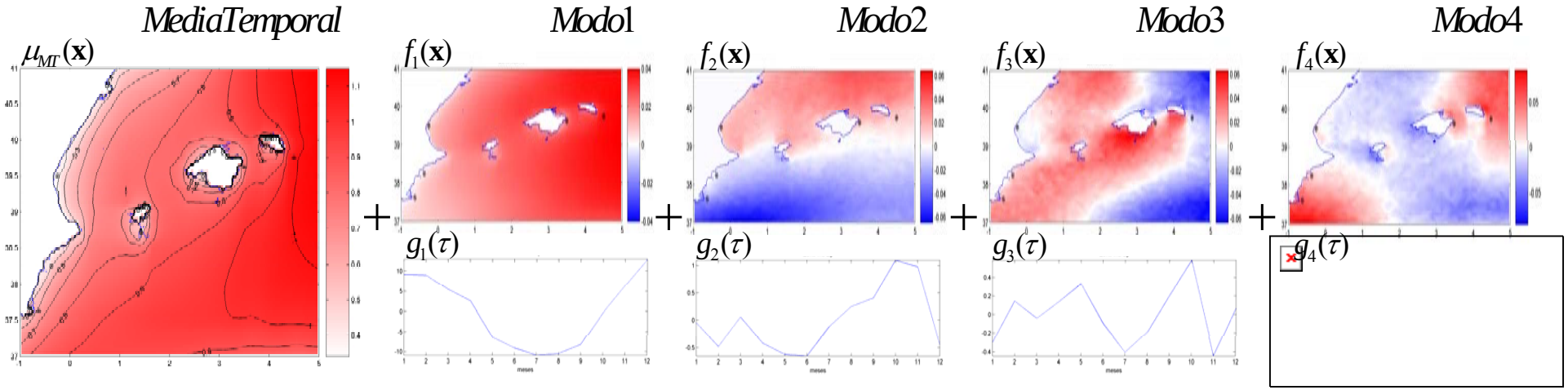
Reanalysis data. Spatial

Monthly distribution (HIPOCAS)

$$Z(\mathbf{x},\tau) \begin{cases} \mu(\mathbf{x},\tau) \longrightarrow 4 \text{ EOF} \\ \sigma(\mathbf{x},\tau) \longrightarrow 4 \text{ EOF} \end{cases} \text{99\%} \Rightarrow Z^*(\mathbf{x},\tau)$$

For instance, for $\mu(\mathbf{x},\tau)$:

$$\mu^*(\mathbf{x},\tau) = \mu_{MT}(\mathbf{x}) + f_1(\mathbf{x})g_1(\tau) + f_2(\mathbf{x})g_2(\tau) + f_3(\mathbf{x})g_3(\tau) + f_4(\mathbf{x})g_4(\tau)$$

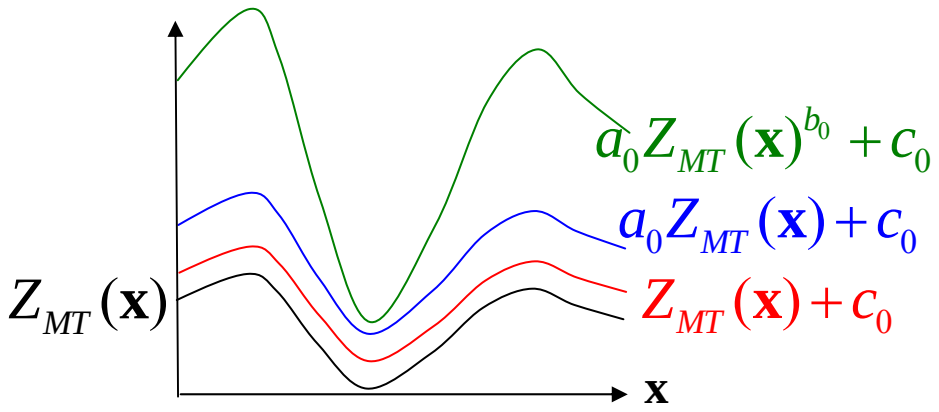


Hypothesis: calibrated value is a linear combination of modes :

$$Z_C(\mathbf{x},\tau) = a_0 Z_{MT}(\mathbf{x})^{b_0} + a_1 f_1(\mathbf{x}) g_1(\tau) \left| g_1(\tau) \right|^{b_1 - 1} + a_2 f_2(\mathbf{x}) g_2(\tau) + a_3 f_3(\mathbf{x}) g_3(\tau) + \\ + a_4 f_4(\mathbf{x}) g_4(\tau) + c_0$$

$\{a_0, a_1, a_2, a_3, a_4, b_0, b_1, c_0\} = \theta$ are the parameters that distort $Z^*(\mathbf{x},\tau)$

For instance, for $Z_{MT}(\mathbf{x})$



CALIBRATION

Reanalysis data. Spatial

$Z_C(\mathbf{x},\tau;\theta)$ (HIPOCAS)

$\theta = \{a_0, a_1, a_2, a_3, a_4, b_0, b_1, c_0\}$ are unknowns

$Z_B(\mathbf{x},\tau)$ (Deep water buoys)

Objective function to minimize: try to minimize the difference between buoy and calibrated hindcast data

$$J(\theta) = \sum_{i=1}^{nb=5} \left\{ \sum_{j=1}^{12} \left\{ \left[\frac{Z_B(\mathbf{x}_i,\tau_j) - Z_C(\mathbf{x}_i,\tau_j;\theta)}{R(\mathbf{x}_i,\tau_j)} \right]^2 P(\mathbf{x}_i,\tau_j) \right\} \right\}$$

Find θ that minimize $J(\theta)$, for $\mu(\mathbf{x},\tau)$ and $\sigma(\mathbf{x},\tau)$

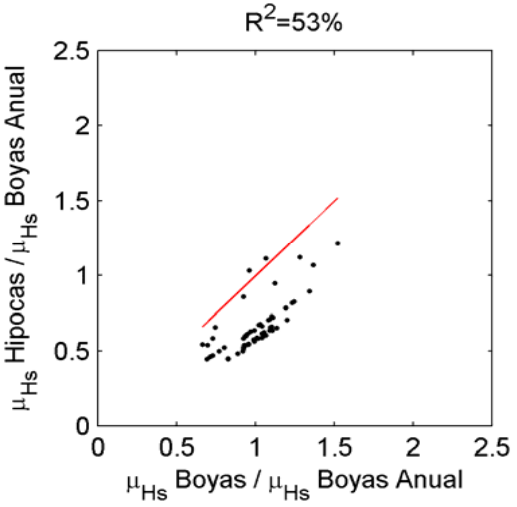
Optimization scheme: **SCE-UA** (Duan et al, 1992)

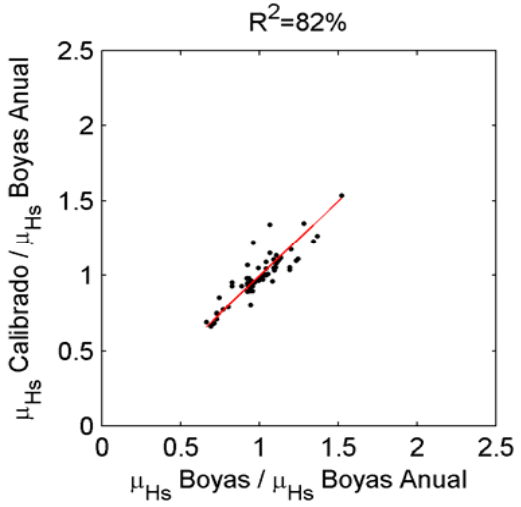
CALIBRATION

Reanalysis data. Spatial

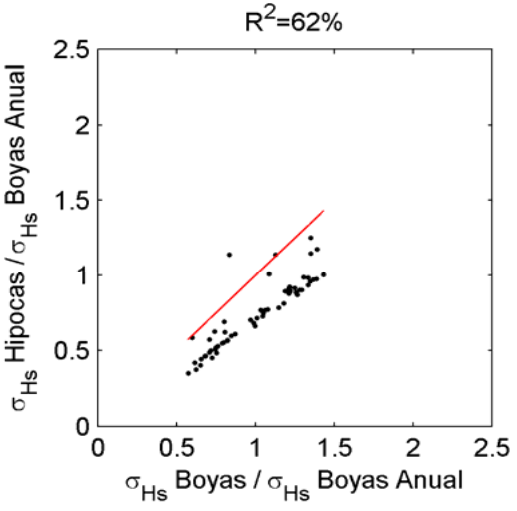
Results in the buoys: Before calibration After calibration

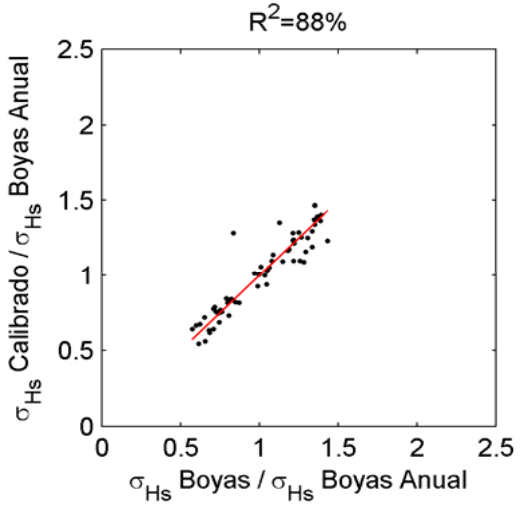
μ :





σ :



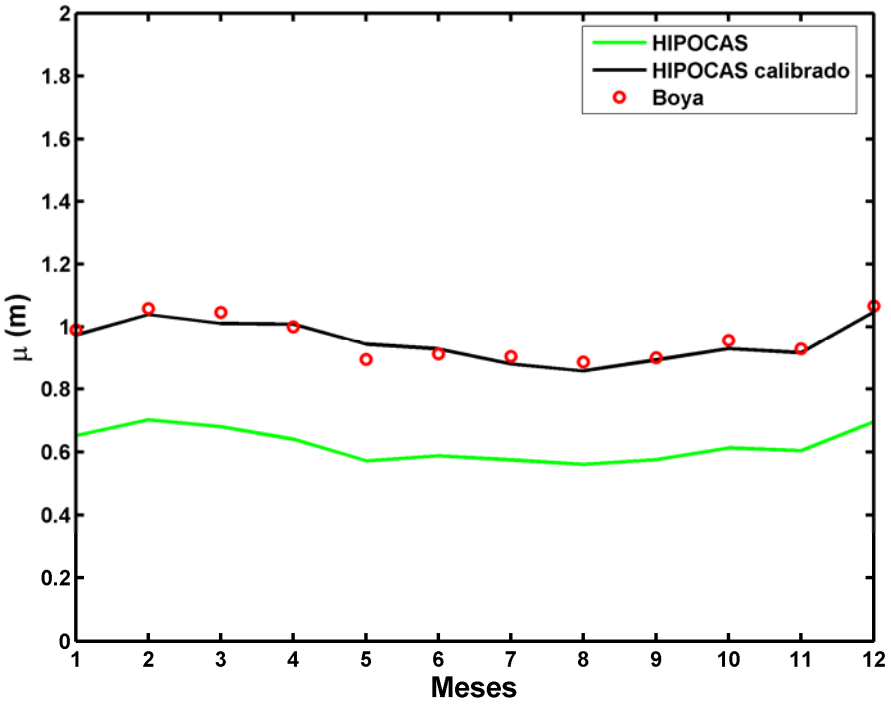


CALIBRATION

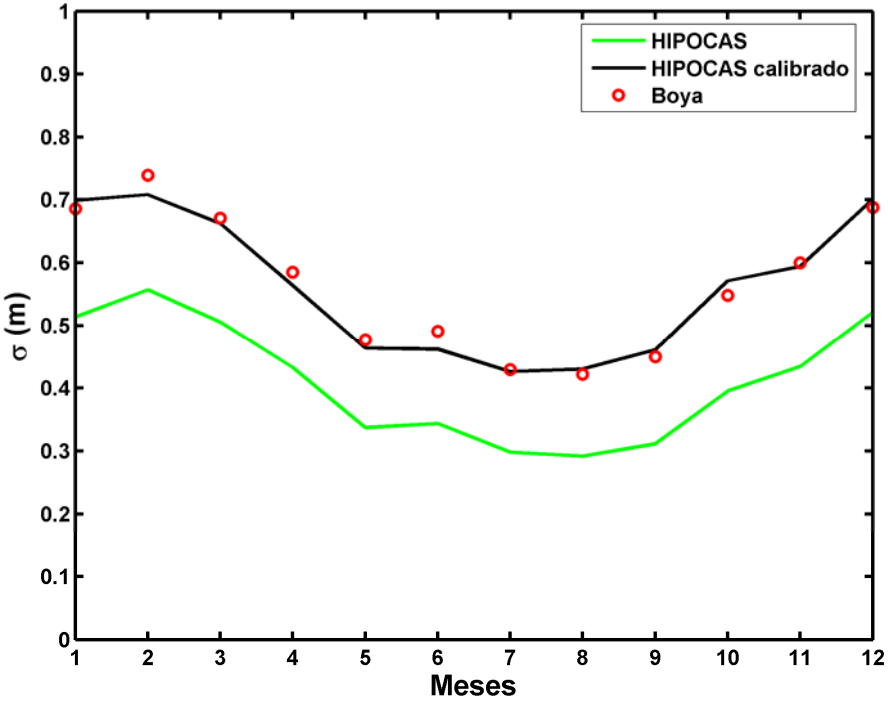
Reanalysis data. Spatial

Calibrated monthly long-term distribution of SWH at the positions of the buoys

$\mu(CaboDePalos, \tau)$

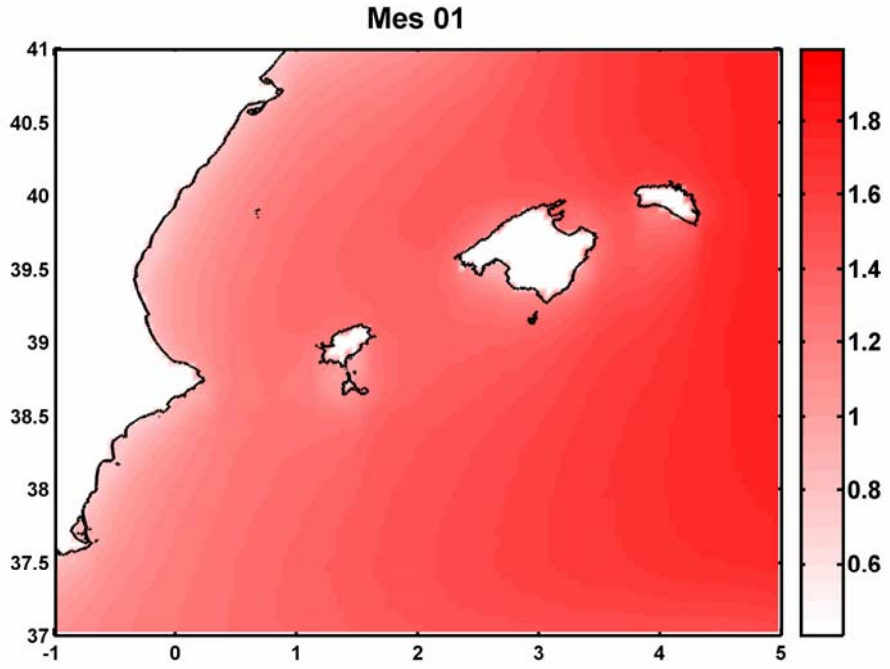


$\sigma(CaboDePalos, \tau)$

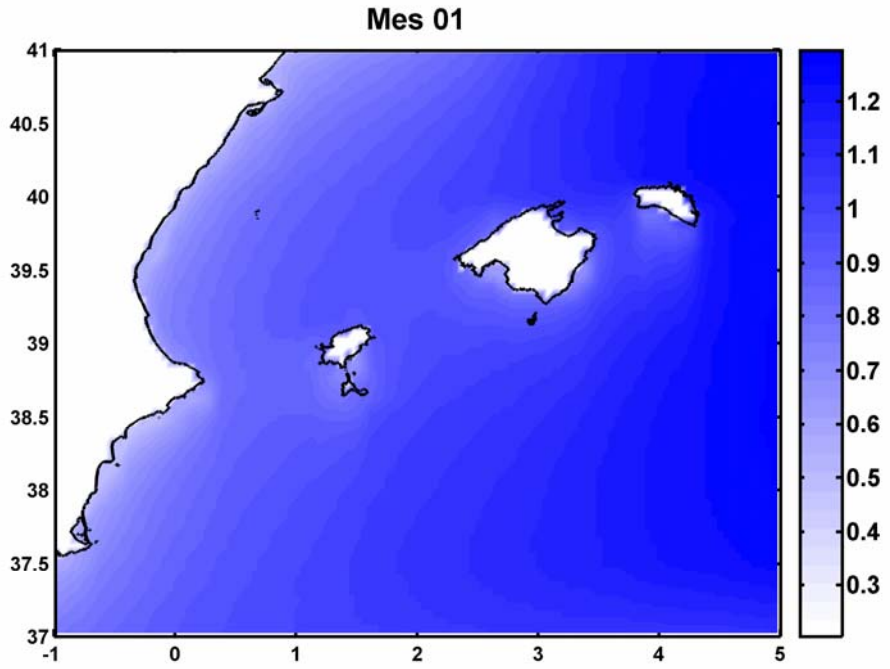


Spatio-temporal variation of calibrated monthly distribution of SWH

$\mu(\mathbf{x},\tau)$



$\sigma(\mathbf{x},\tau)$



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1. **Introduction**

2. Calibration
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3. **Time series recovering**

4. Validation

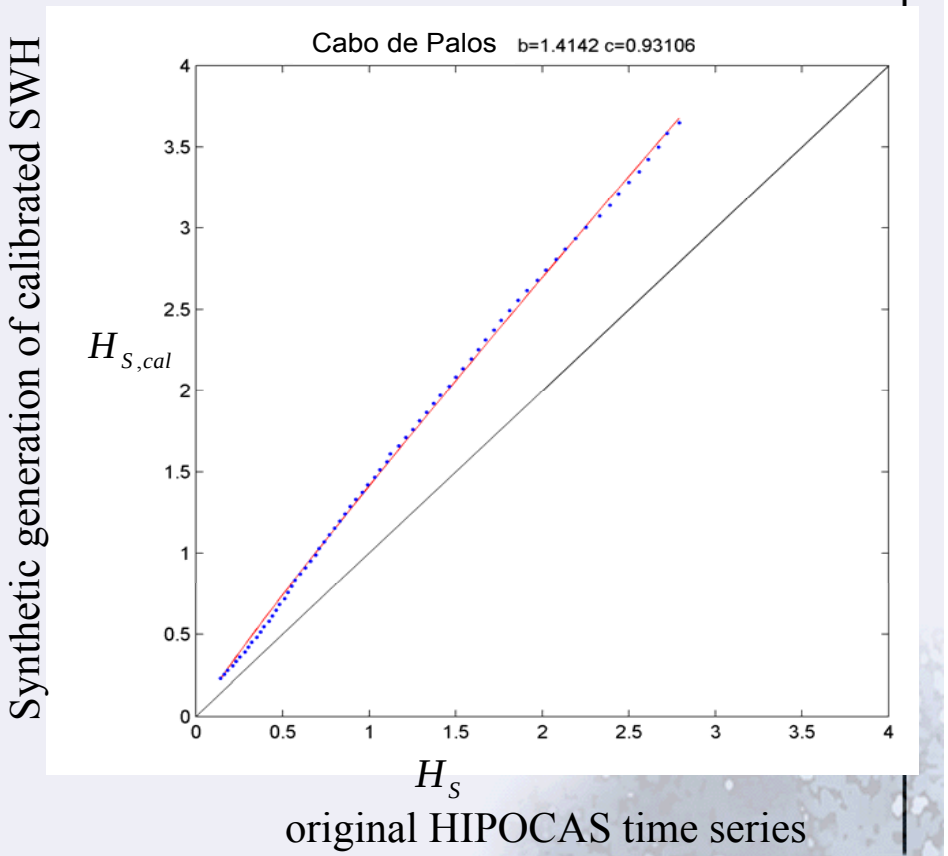
5. Conclusions

Synthetic generation of SWH from the calibrated monthly long-term distribution comparing with the original HIPOCAS time series (QQ-Plot)

$$H_{S,cal}(\mathbf{x}) = a(\mathbf{x}) + b(\mathbf{x}) H_S(\mathbf{x})^{c(\mathbf{x})}$$

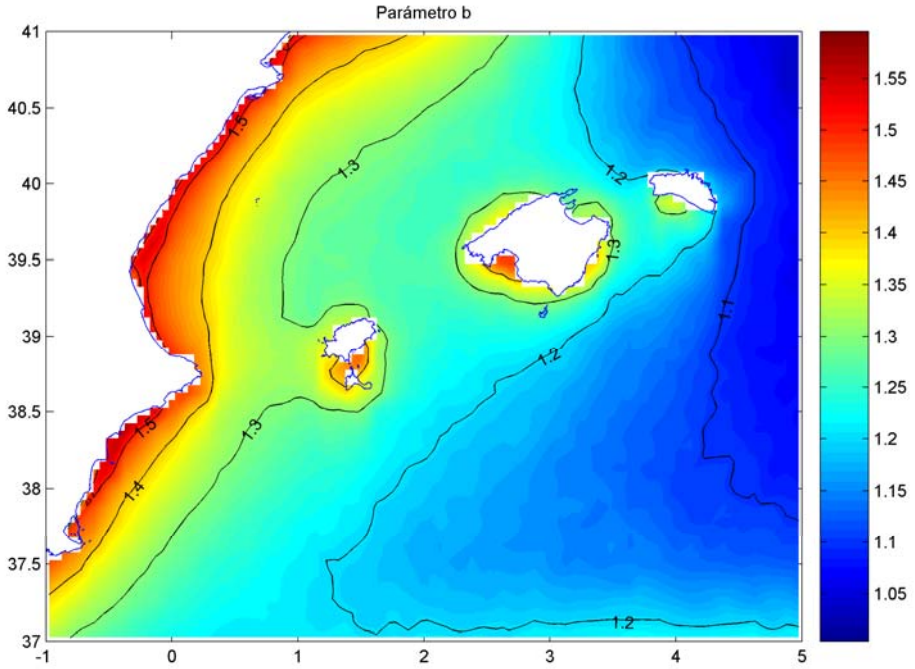
$$a(\mathbf{x}) = 0$$
$$b(\mathbf{x})$$
$$c(\mathbf{x})$$

Final parameters

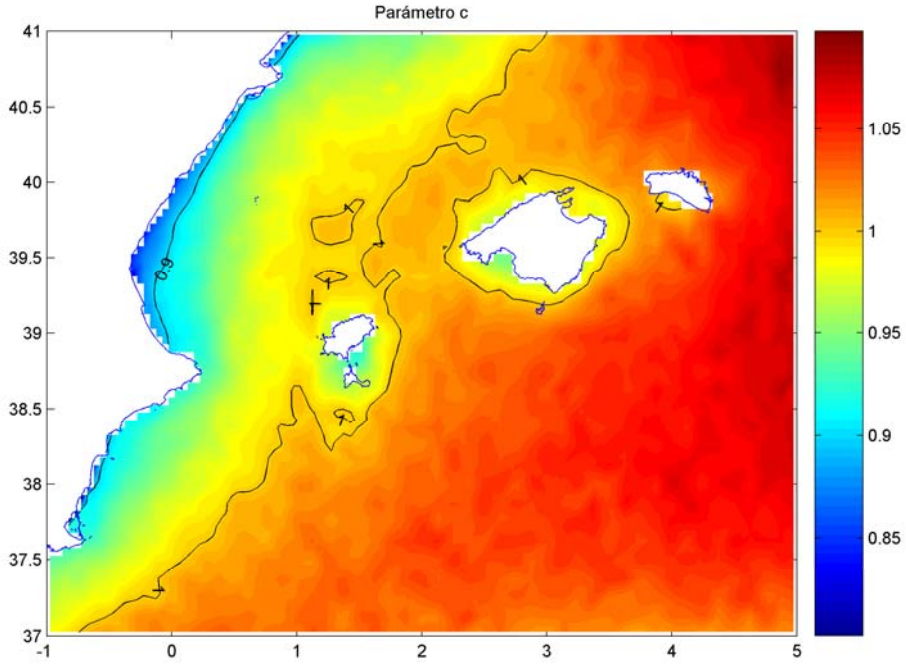


Final parameters of the spatial calibration

$b(\mathbf{x})$



$c(\mathbf{x})$



$$H_{S,cal}(\mathbf{x}) = b(\mathbf{x}) H_S(\mathbf{x})^{c(\mathbf{x})}$$

CALIBRATION

Reanalysis data. Spatial

1. Introduction
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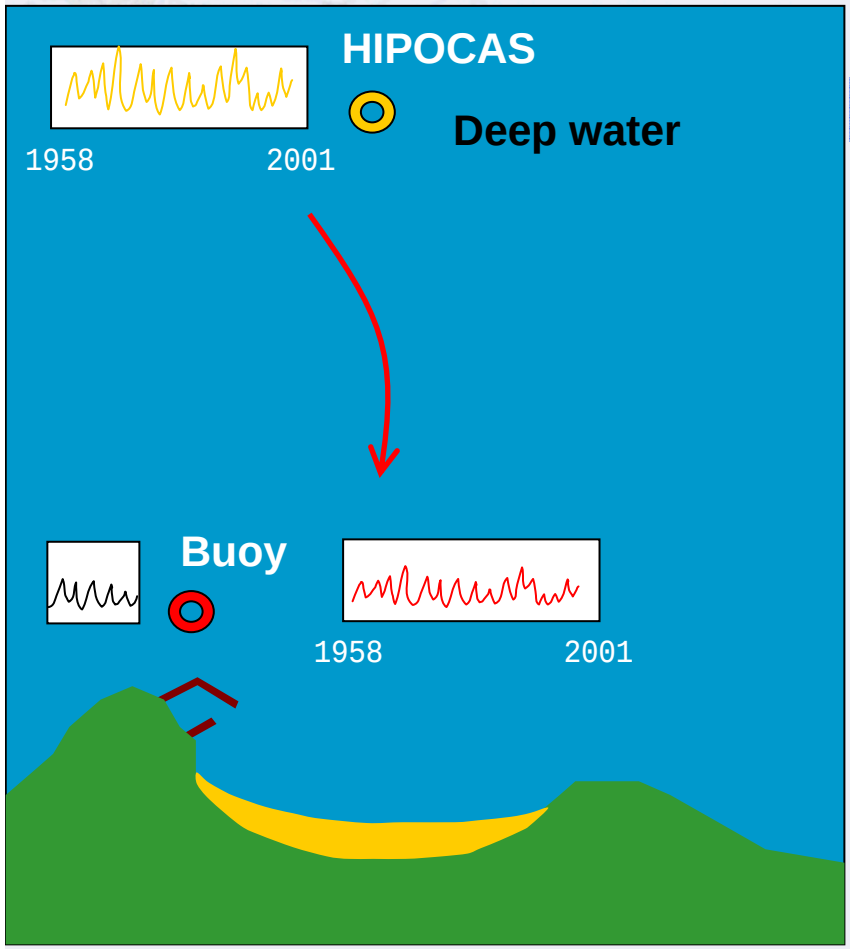
CALIBRATION

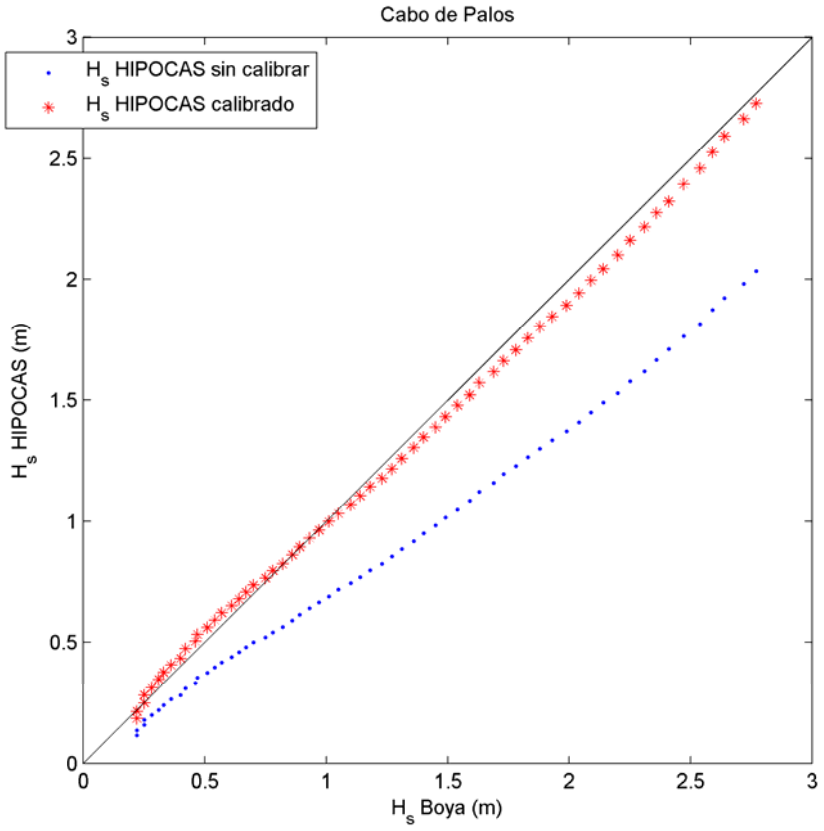
Reanalysis data. Spatial

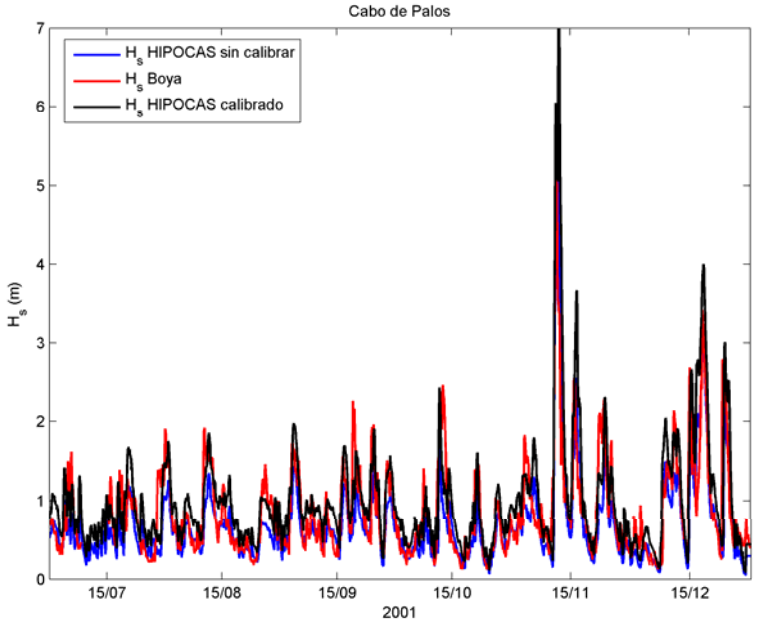
Validation in the location of the buoys: wave climate propagation



WAVE CLIMATE PROPAGATION

Validation in the location of the buoys: wave climate propagation



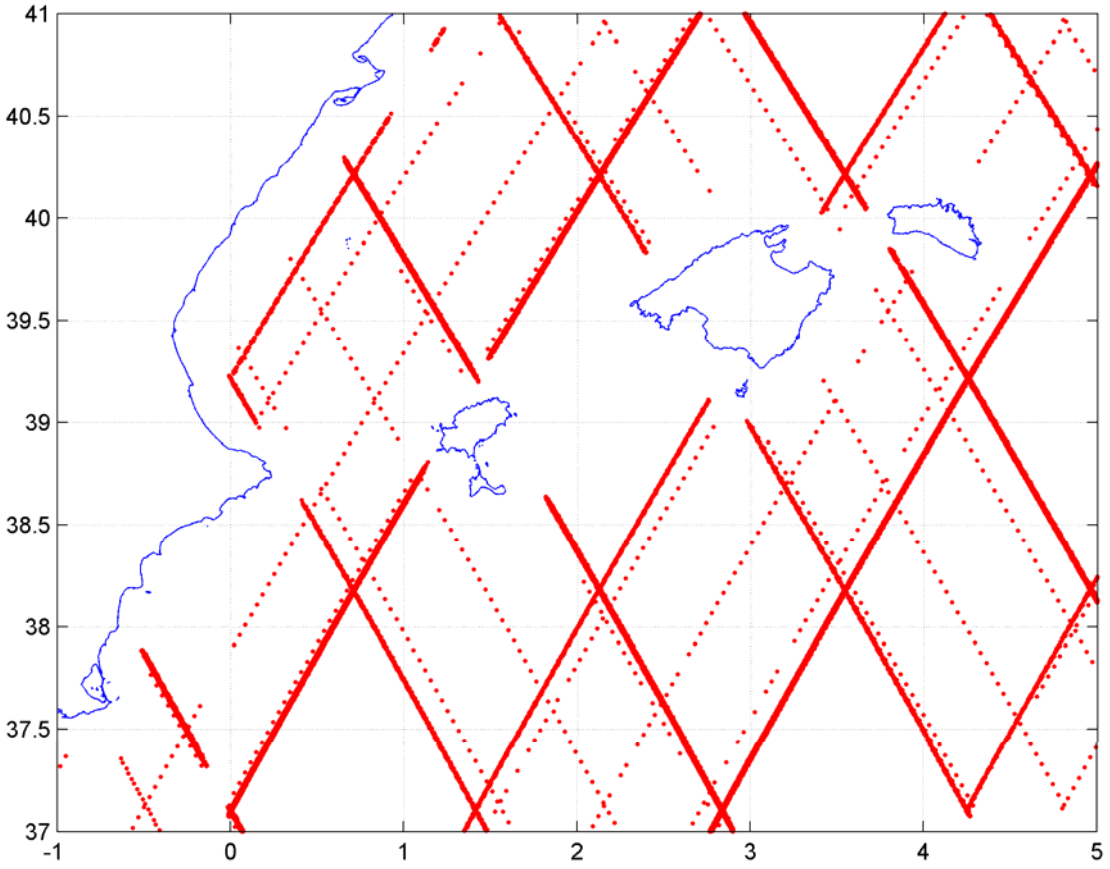


Validation using satellite data base from Altimeter TOPEX/POSEIDON.

Mesh 1ºx1º

1997-2003

QQ plot



CALIBRATION

Reanalysis data. Spatial

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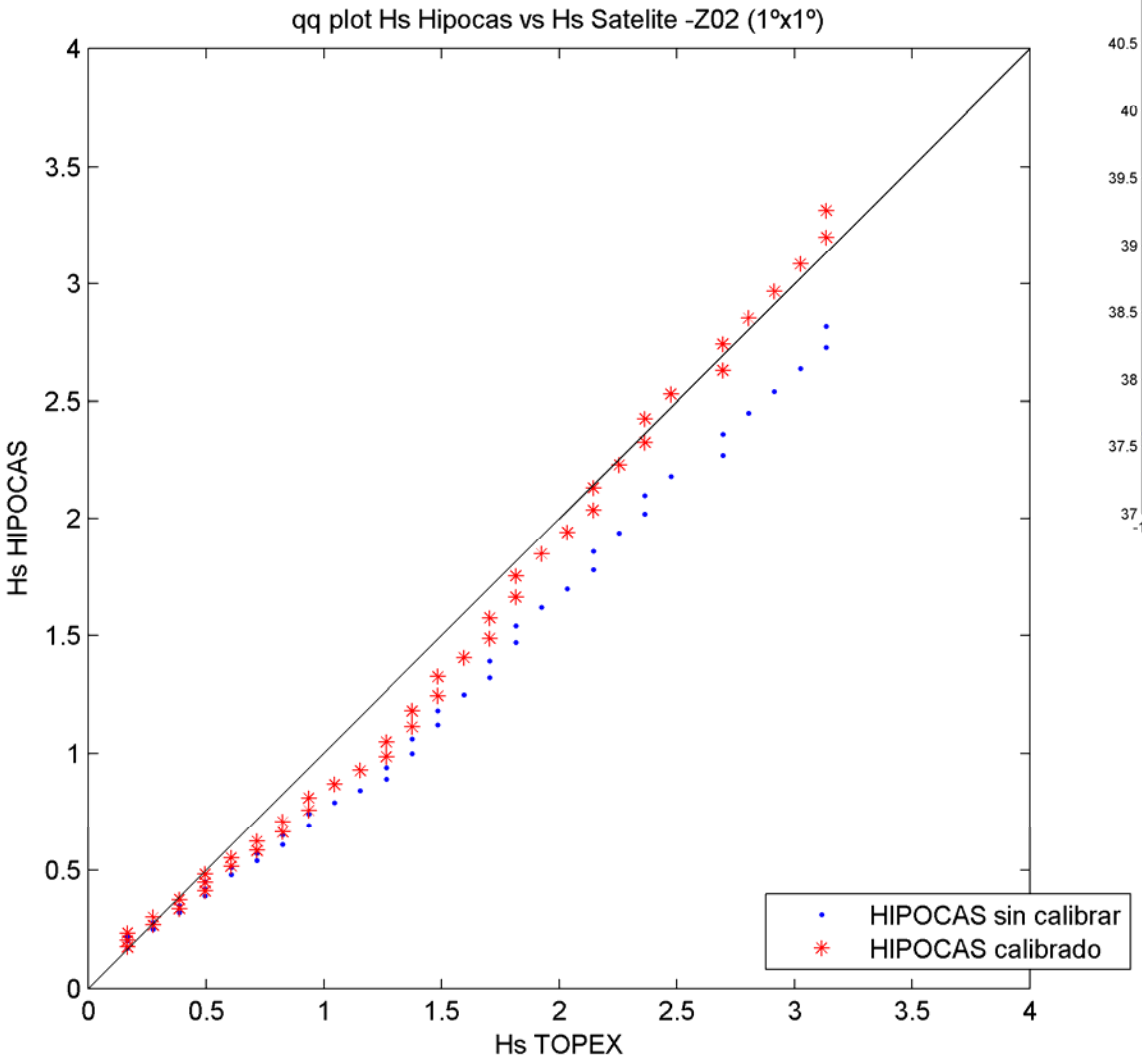
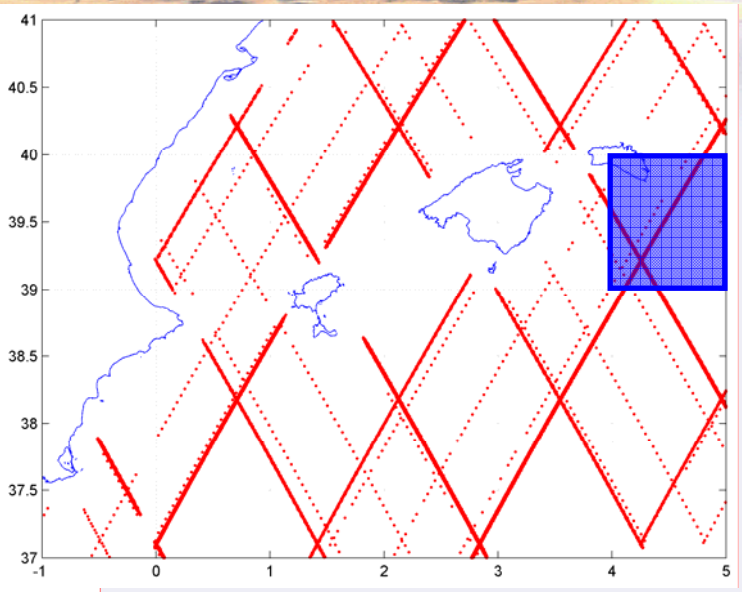
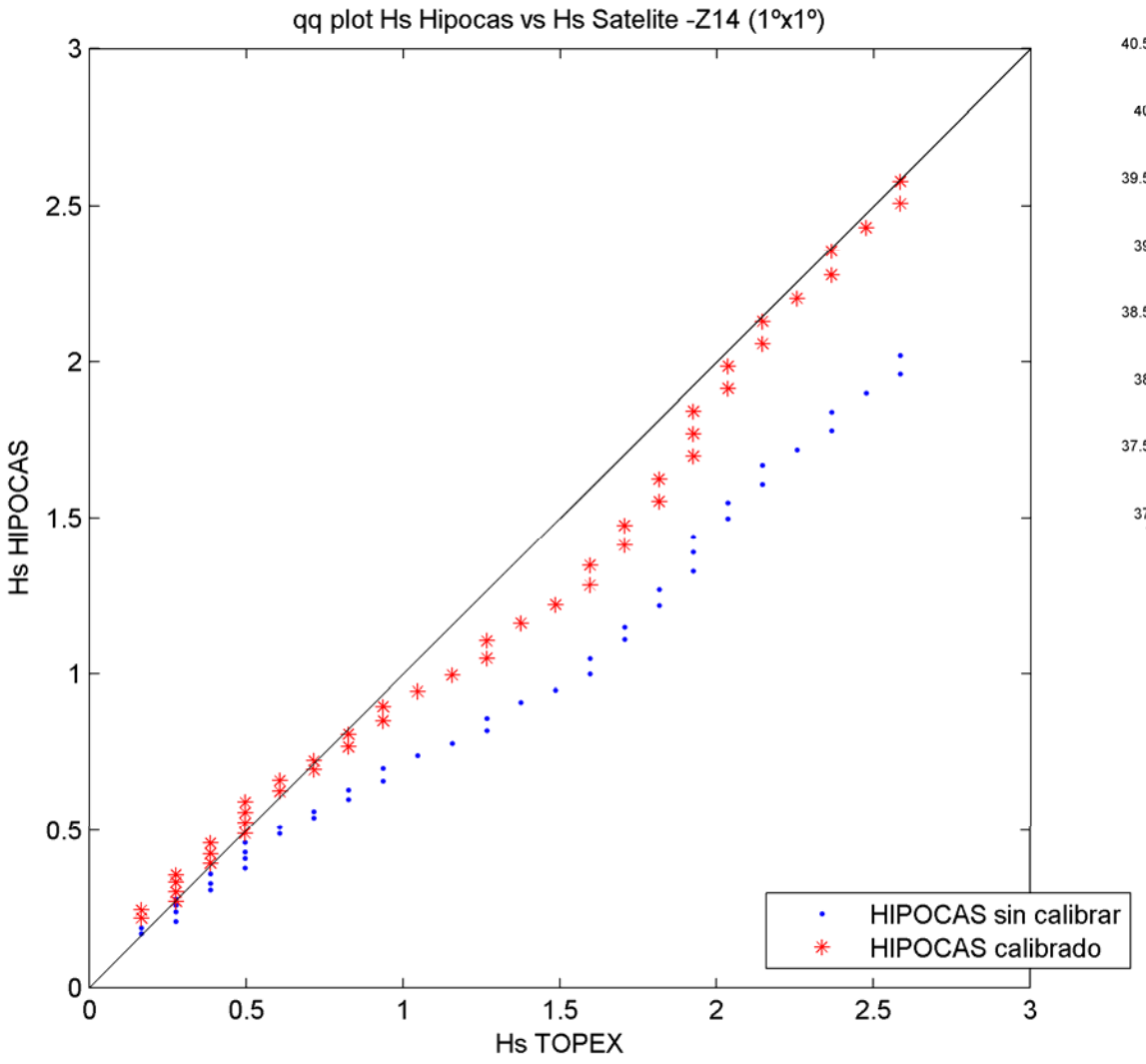
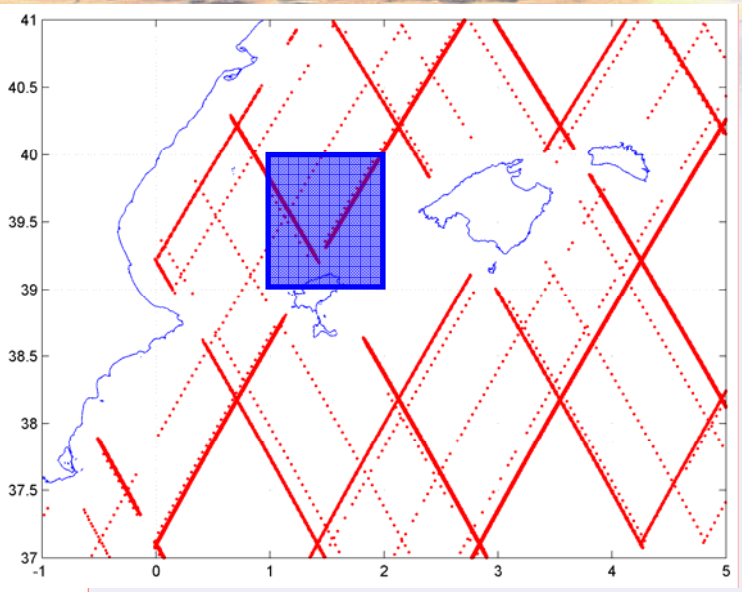




CALIBRATION

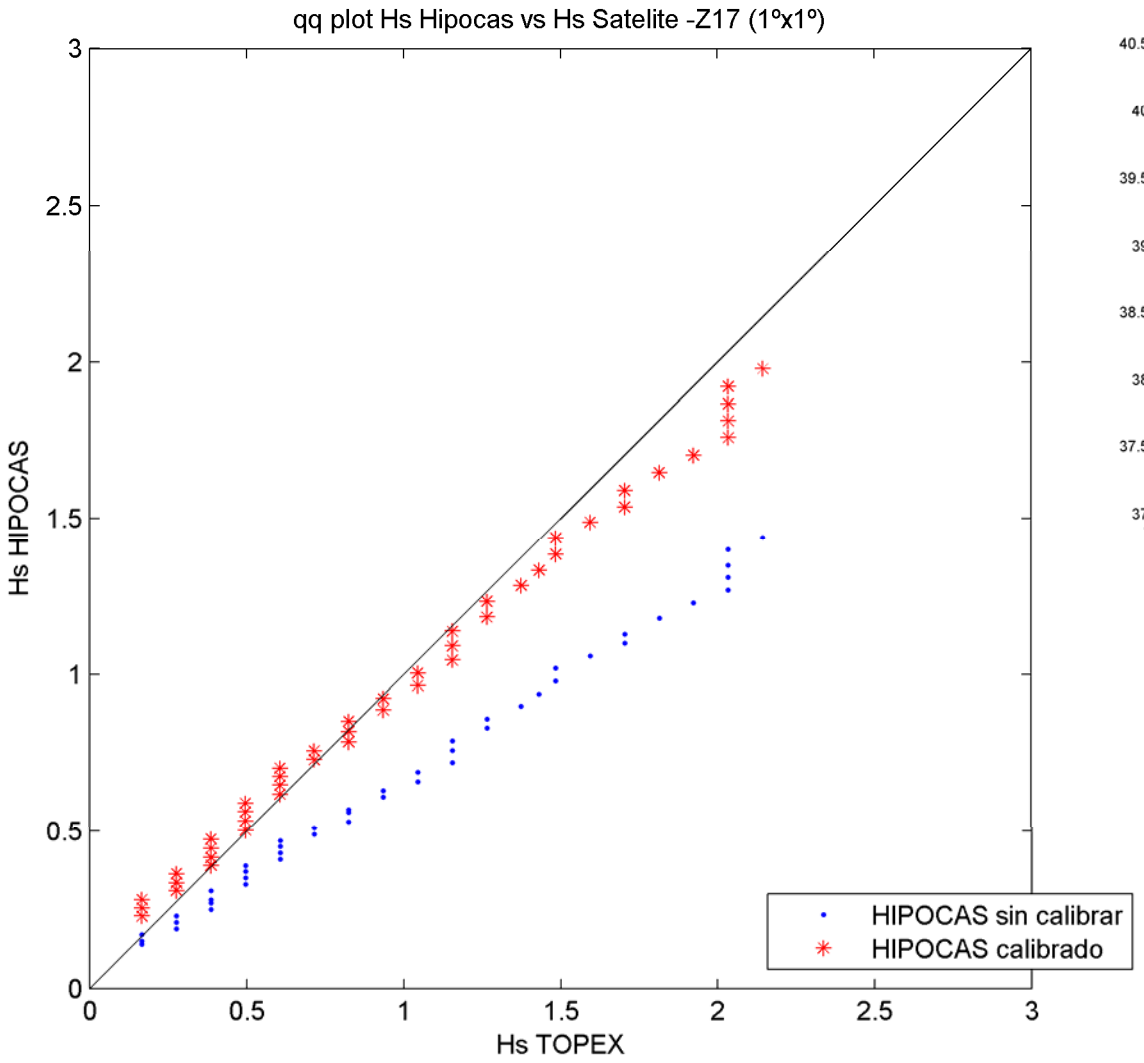
Reanalysis data. Spatial

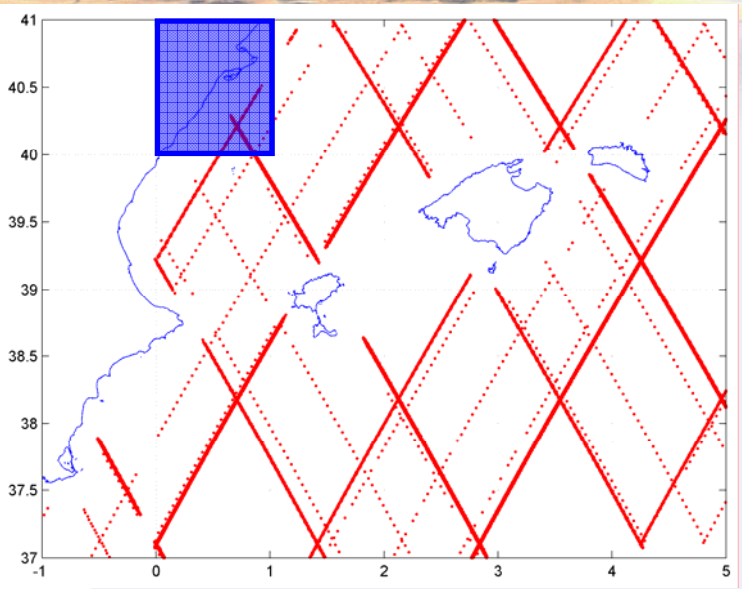




CALIBRATION

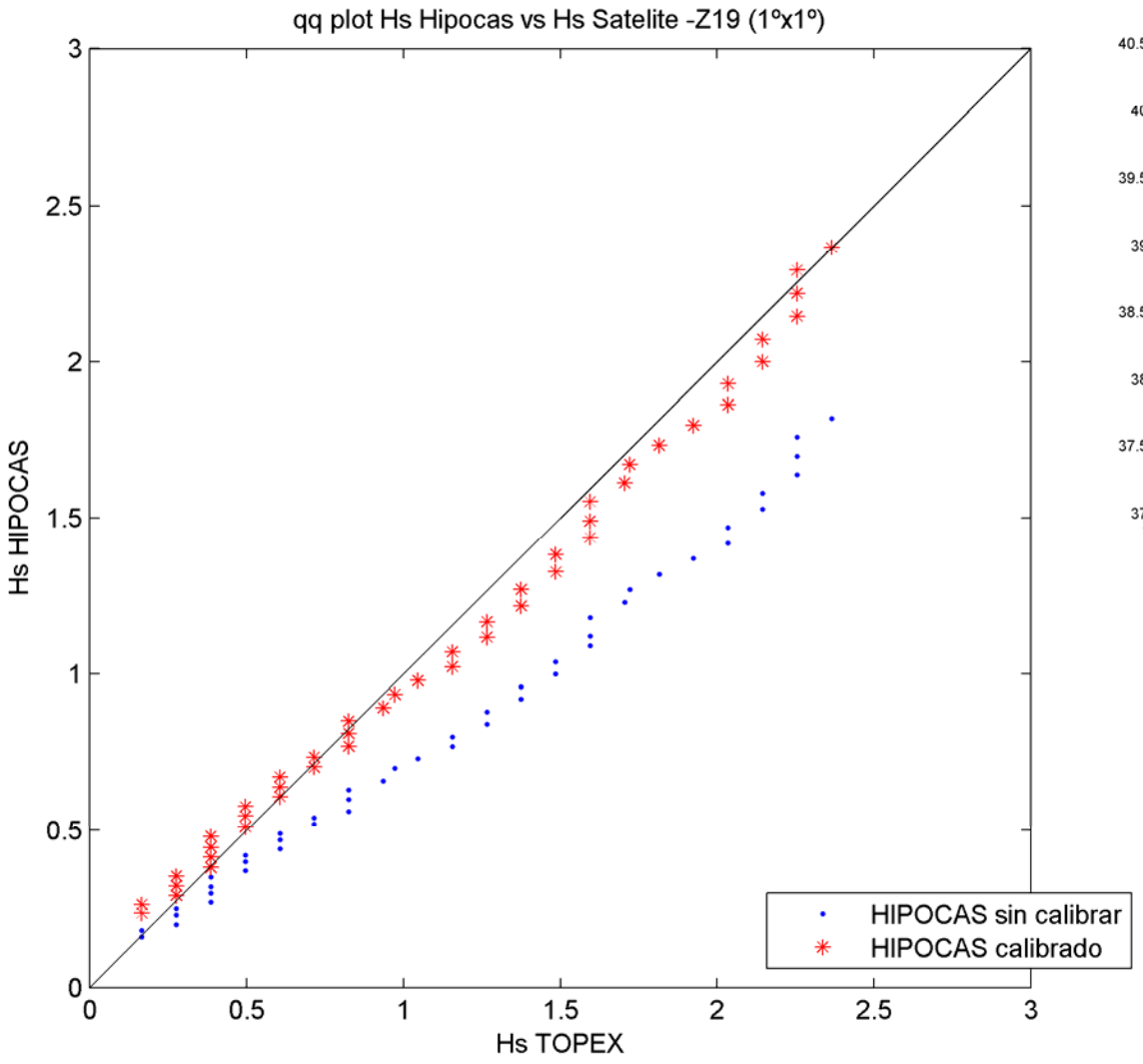
Reanalysis data. Spatial

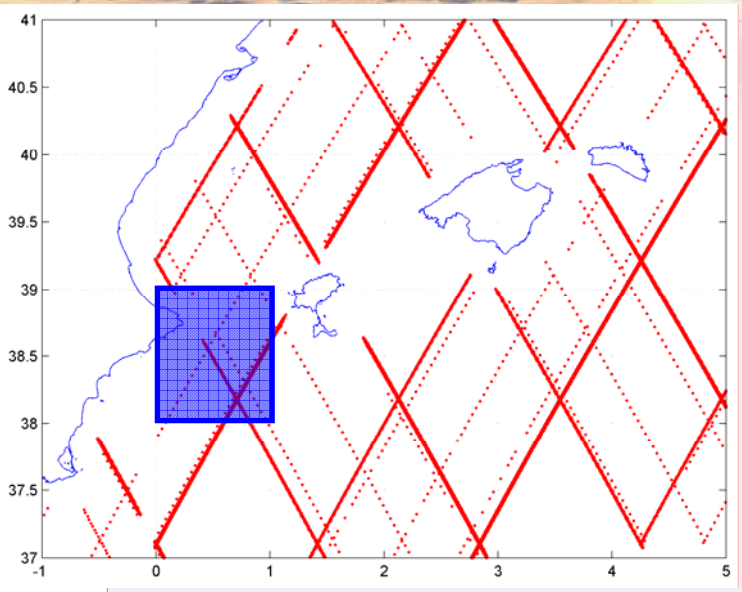




CALIBRATION

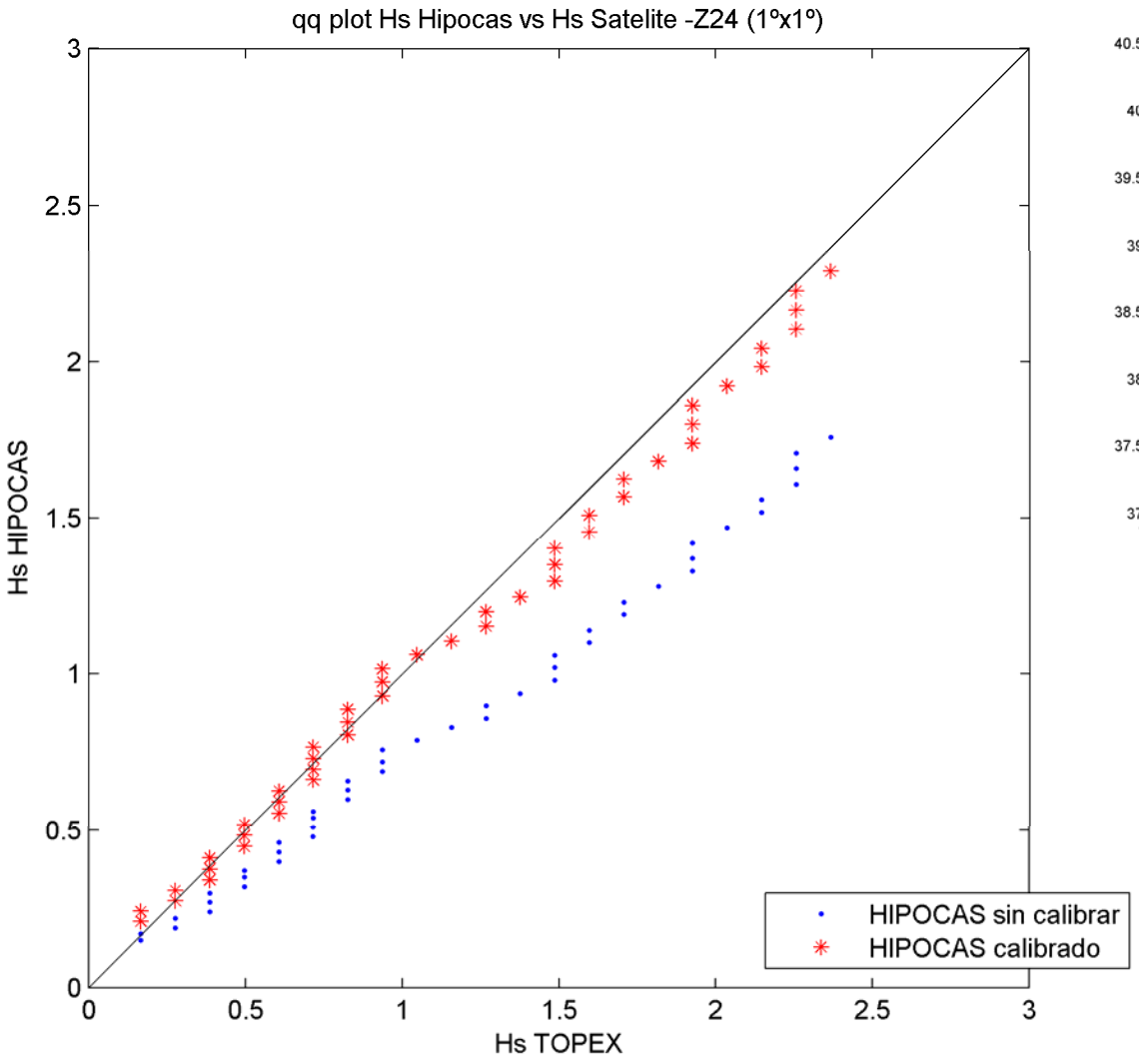
Reanalysis data. Spatial

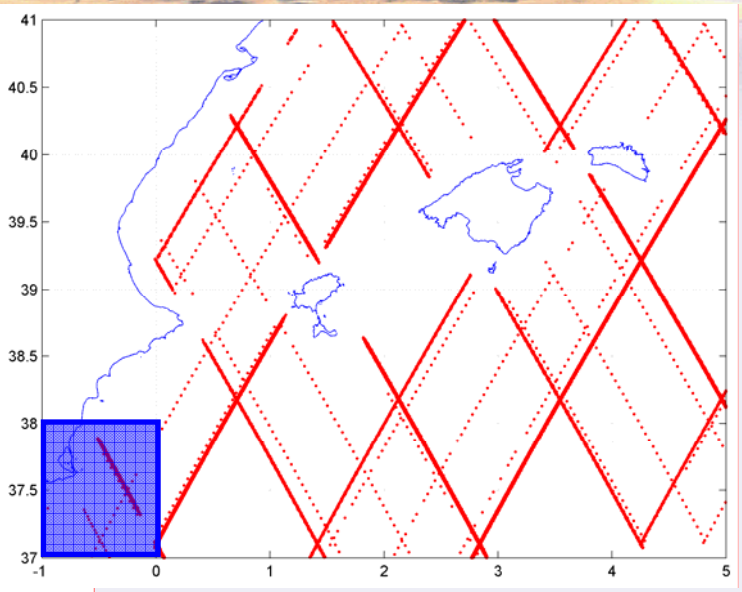




CALIBRATION

Reanalysis data. Spatial





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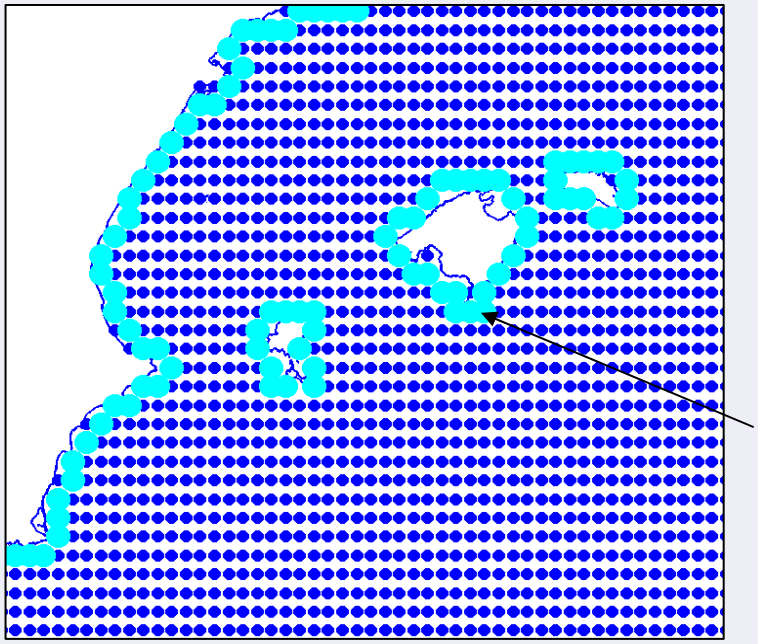
1. **Introduction**
2. Calibration
   1. Methodology
   2. Results
3. Time series recovering
4. Validation
5. **Conclusions**

CALIBRATION

Reanalysis data. Spatial

•This methodology results in a calibrated data base that can be used as "**numerical buoys**", providing

- a good spatial description of long-term and extreme value distributions of wave climate
- an excellent data base for climatic studies



Every particular point can be considered as a numerical deep water directional buoy

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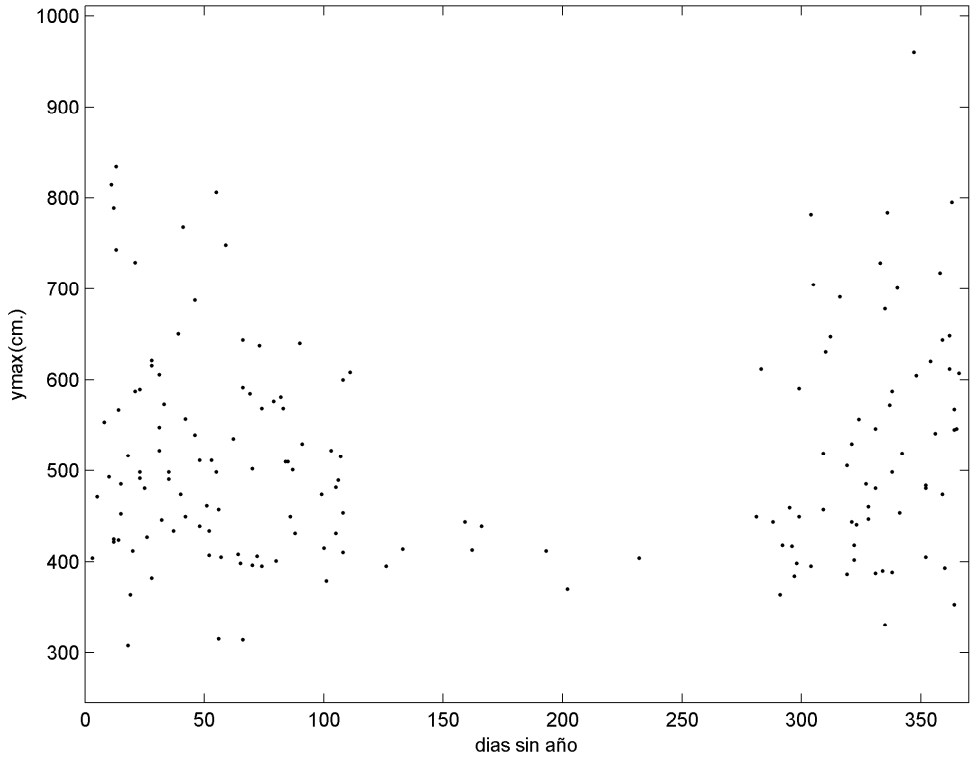
Time-scales of interest

Seasonal

Interdecadal

Secular

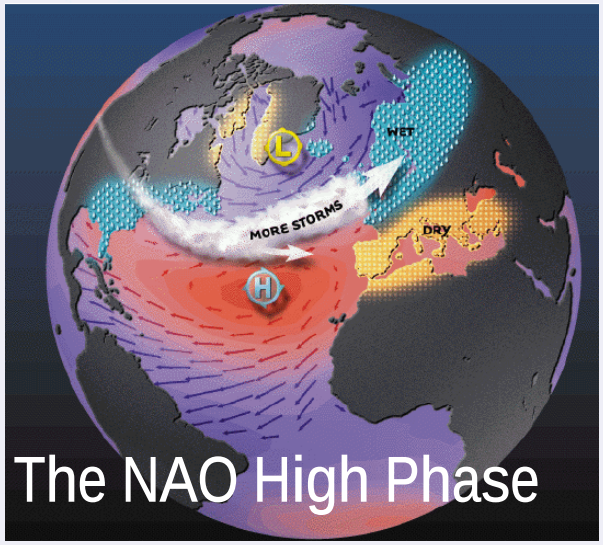


Time-scales of interest

Seasonal

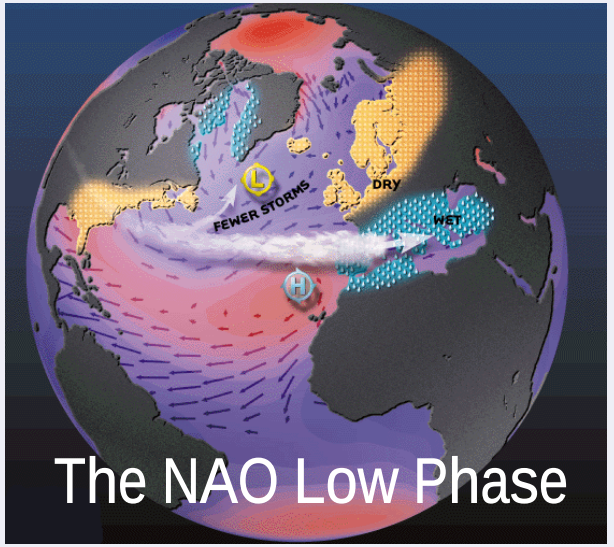
Interdecadal

Secular



The NAO High Phase

- Stronger subtropical high
- Deeper Icelandic Low
- Increased pressure difference
- Stronger storms move north
- Warm & wet winters in Europe
- Cold & dry winters in Canada
- Mild & wet winters in East US
- Intense “vortex” (circumpolar winds in stratosphere)



The NAO Low Phase

- Weak Icelandic low
- Weak subtropical high
- Less Pressure difference
- Fewer storms move west
- Mediterranean is moist
- Northern Europe is cold
- US east cost is cold & snowy
- Weak stratospheric polar vortex

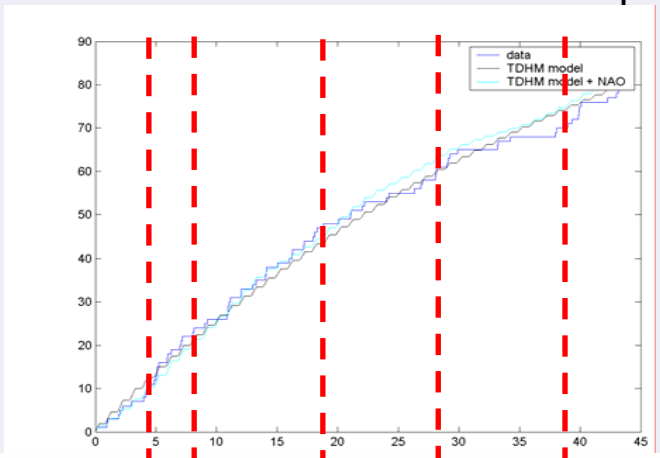
Time-scales of interest

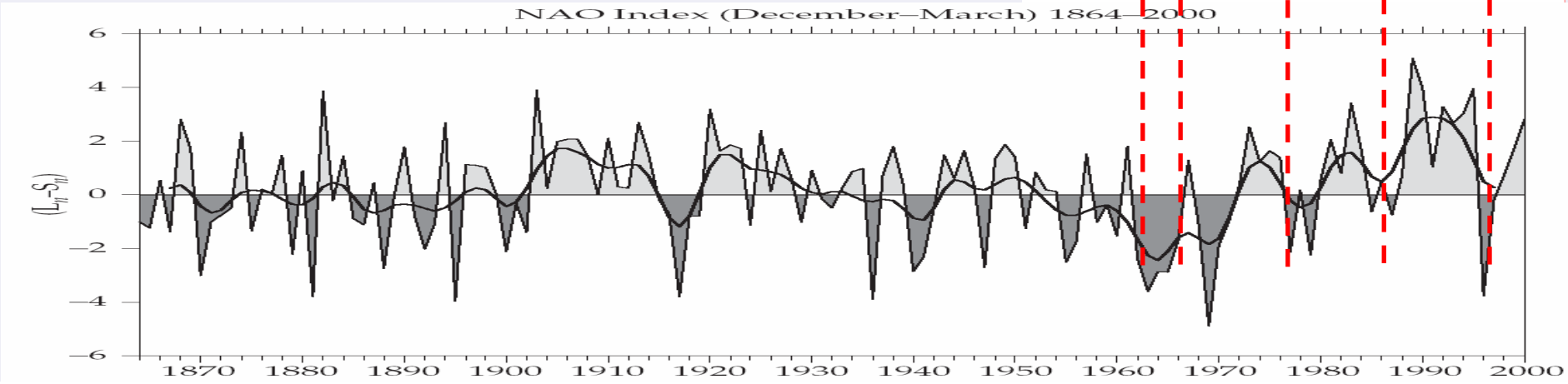
- Higher rate of ocurrence of extreme events in the Mediterranean during a negative NAO phase

Seasonal

Interdecadal

Secular



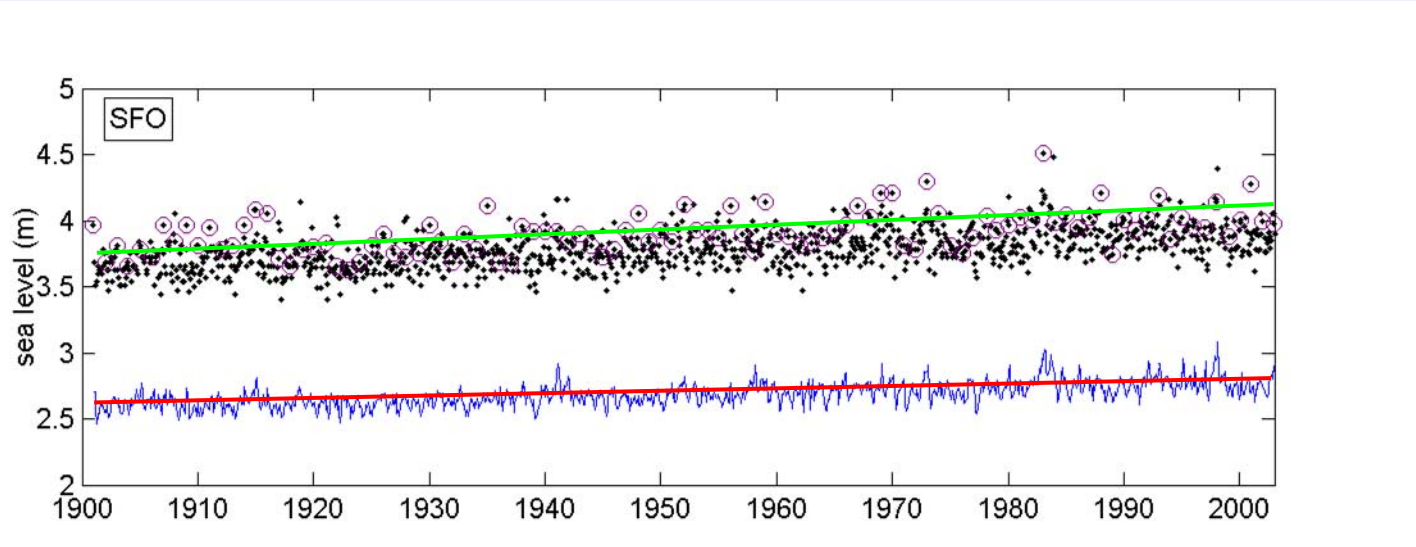


Time-scales of interest

Seasonal

Interdecadal

Secular



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SCALAR VARIABLES

• We calculate the monthly ***Hs*** long- term distributions assuming that are Log-Normal distributed

• Parameters: μ, σ.

$$f(Hs;\mu,\sigma) = \frac{1}{Hs\sigma\sqrt{2\pi}} \exp\left[\frac{-(\ln(Hs)-\mu)^2}{2\sigma^2}\right]$$

↓

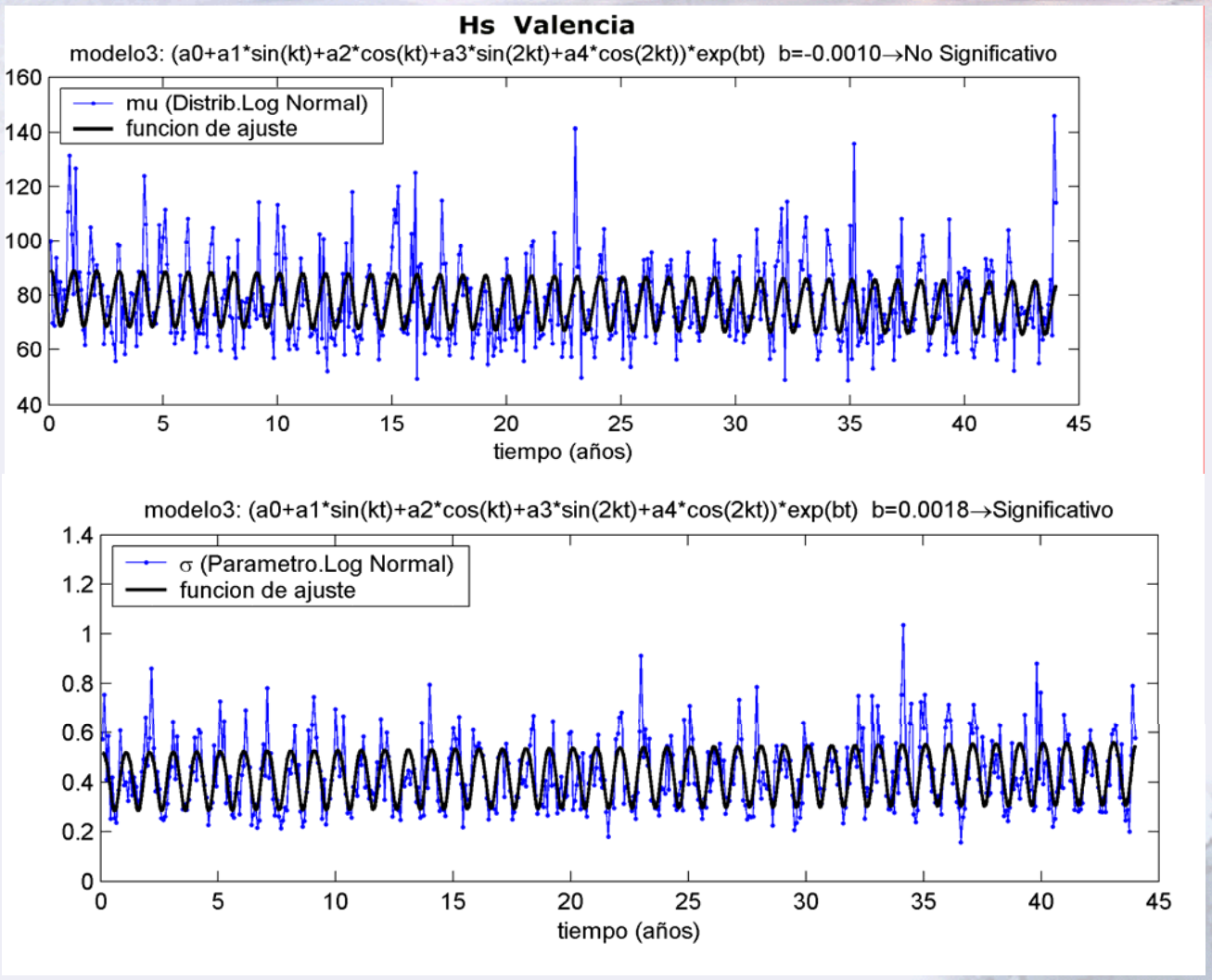
Time unit = 1 month

↓

We fit a non-linear model including seasonality and a long-term trend:

$$\left[\beta_0 + \beta_1 \cdot sen(kt) + \beta_2 \cos(kt) + \beta_3 sen(2kt) + \beta_4 \cos(2kt)\right] \cdot e^{\beta_5 t}$$

Model fit


Hs Valencia
modelo3: (a0+a1*sin(kt)+a2*cos(kt)+a3*sin(2kt)+a4*cos(2kt))*exp(bt) b=-0.0010→No Significativo
mu (Distrib.Log Normal)
funcion de ajuste
160
140
120
100
80
60
40
0
5
10
15
20
25
30
35
40
45
tiempo (años)
modelo3: (a0+a1*sin(kt)+a2*cos(kt)+a3*sin(2kt)+a4*cos(2kt))*exp(bt) b=0.0018→Significativo
σ (Parametro.Log Normal)
funcion de ajuste
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
tiempo (años)

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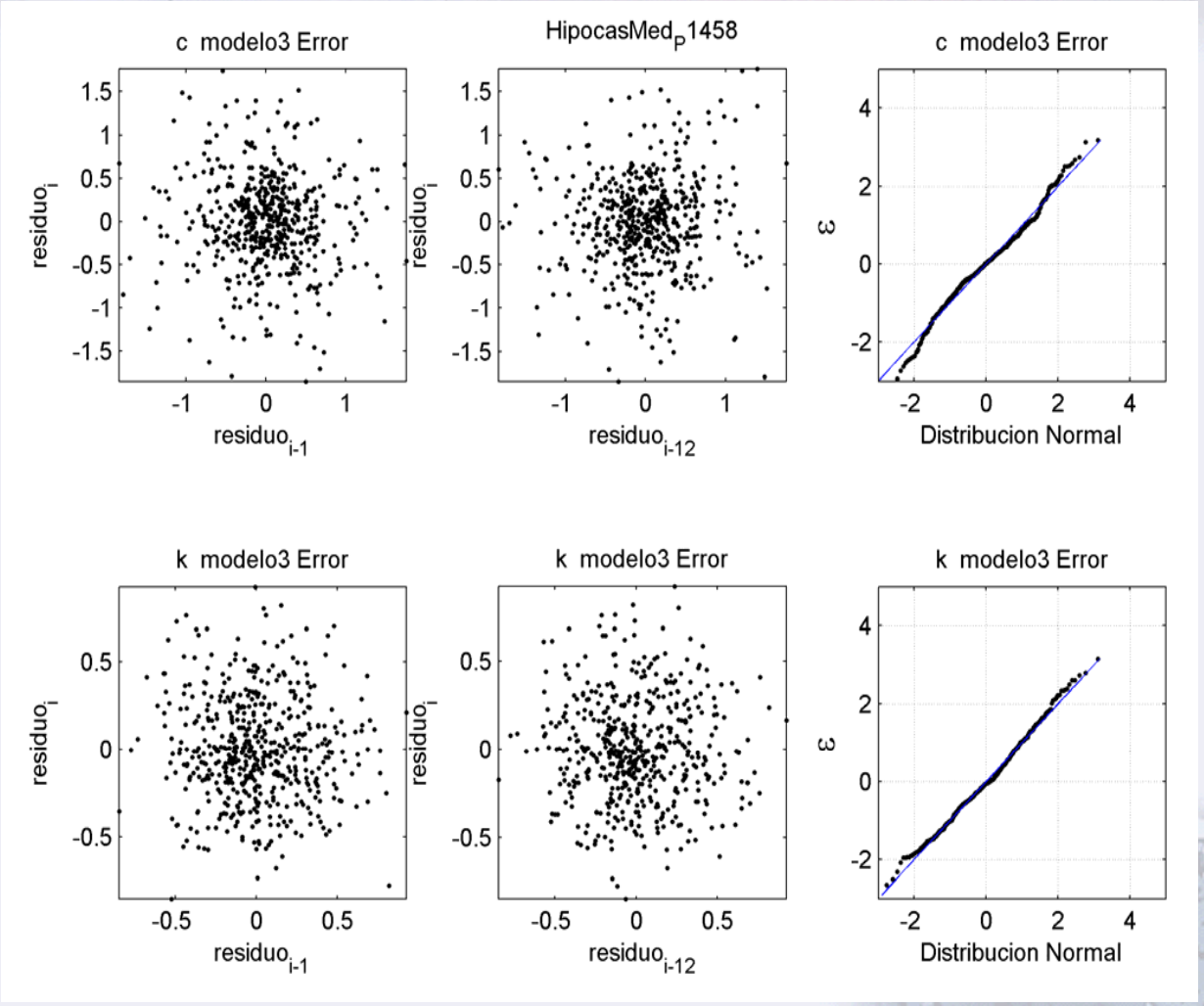
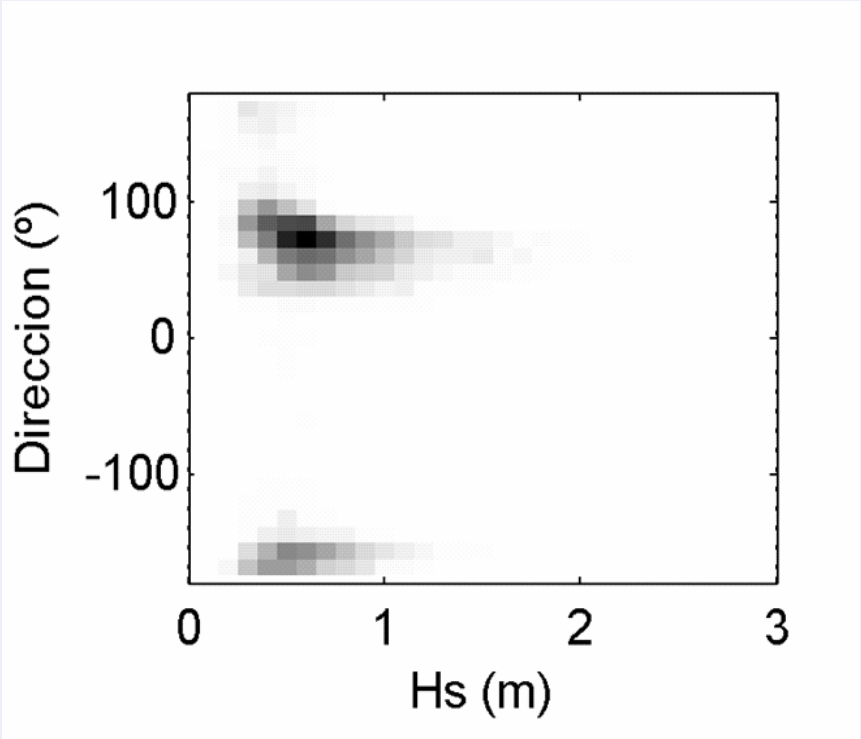
Goodness of fit

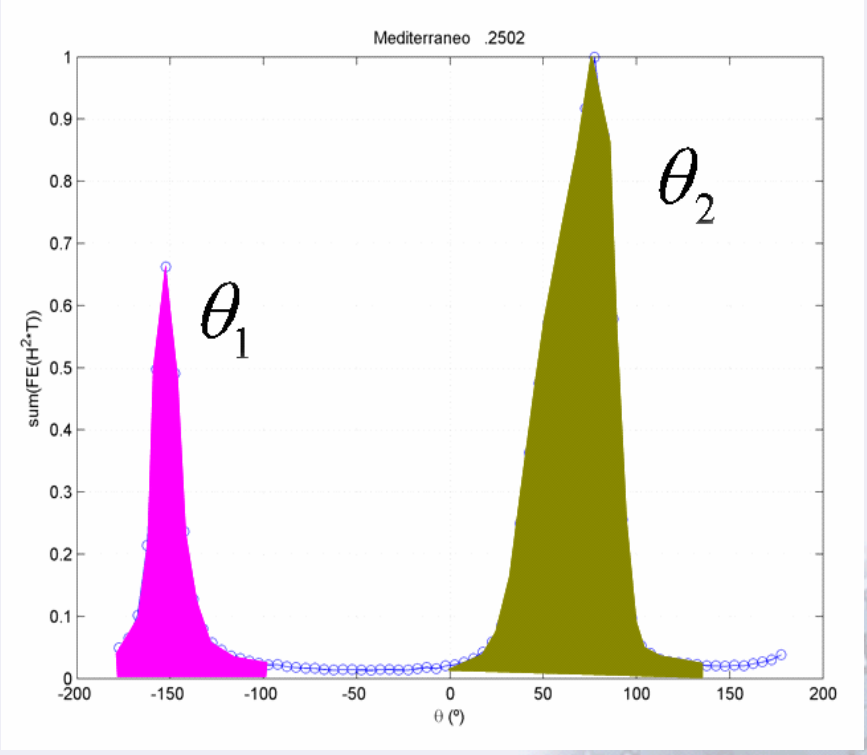


DIRECTIONAL VARIABLES

$$\overrightarrow{F_E} = \frac{1}{8}\rho g H^2 \overrightarrow{c_g} = \frac{1}{8}\rho g H^2 c_g (\cos\theta_H \vec{i} + \sin\theta_H \vec{j})$$

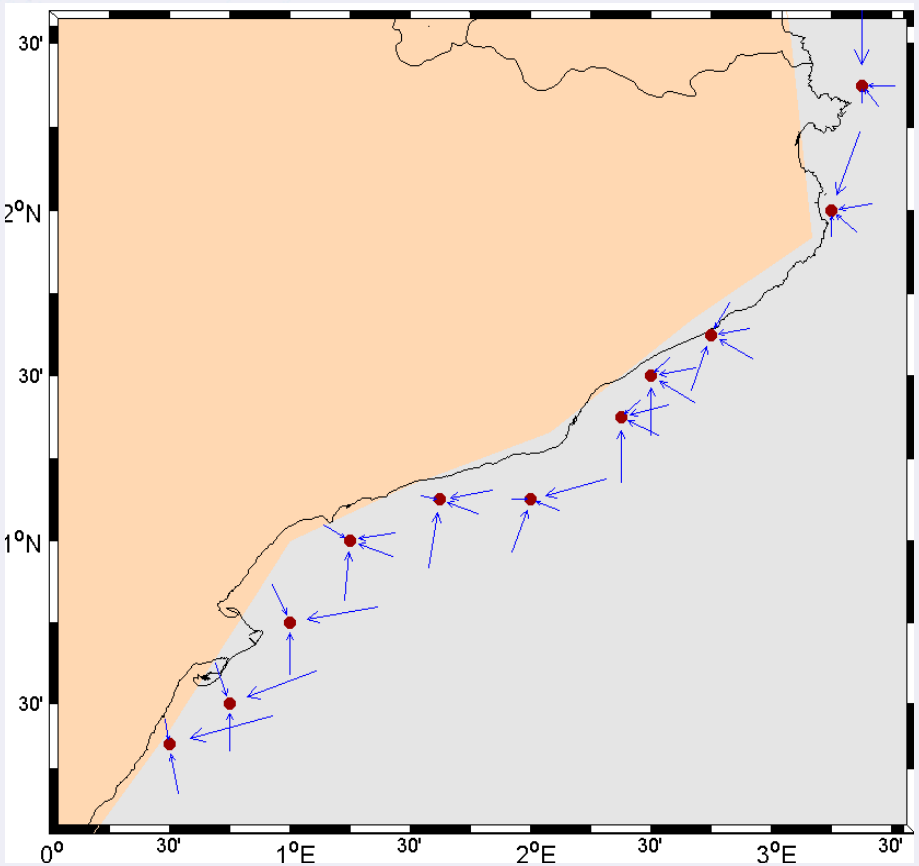


Joint pdf *(Hs,θ)*



Proportion of energy against the direction

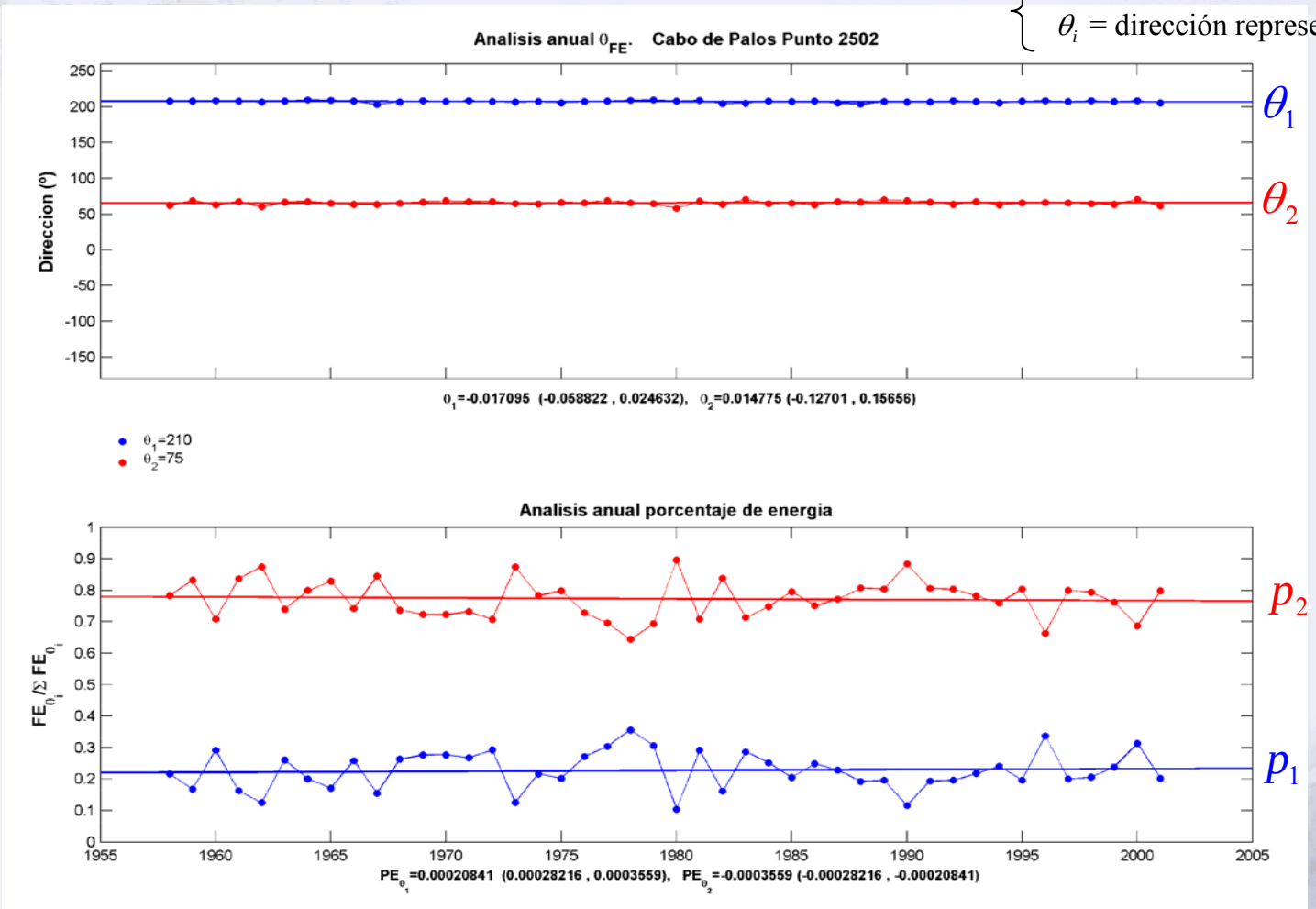
DIRECTIONAL VARIABLES



"Wave families"

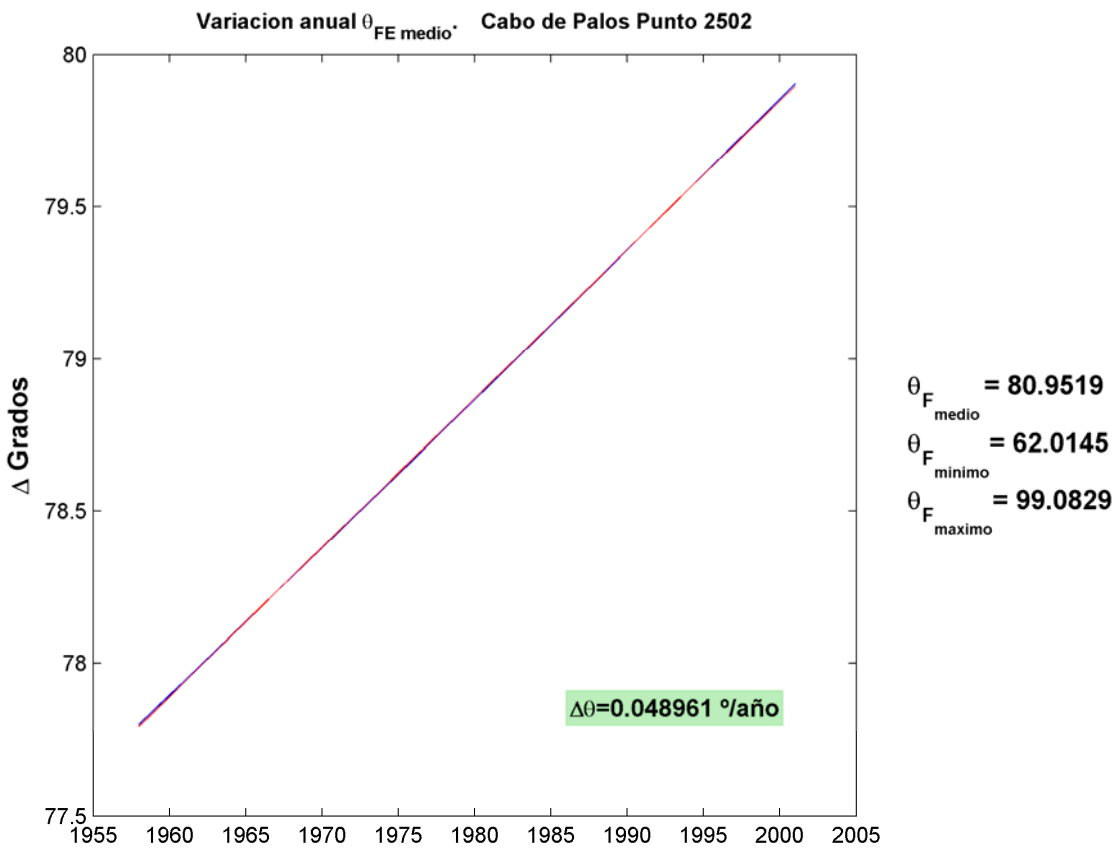
DIRECTIONAL VARIABLES

p_i = porcentaje de energía de cada familia.
θ_i = dirección representativa de cada familia.



DIRECTIONAL VARIABLES

$$\theta = \arctan\left(\frac{\sum_{i=1}^{n} p_i \sin\theta_i}{\sum_{i=1}^{n} p_i \cos\theta_i}\right)$$



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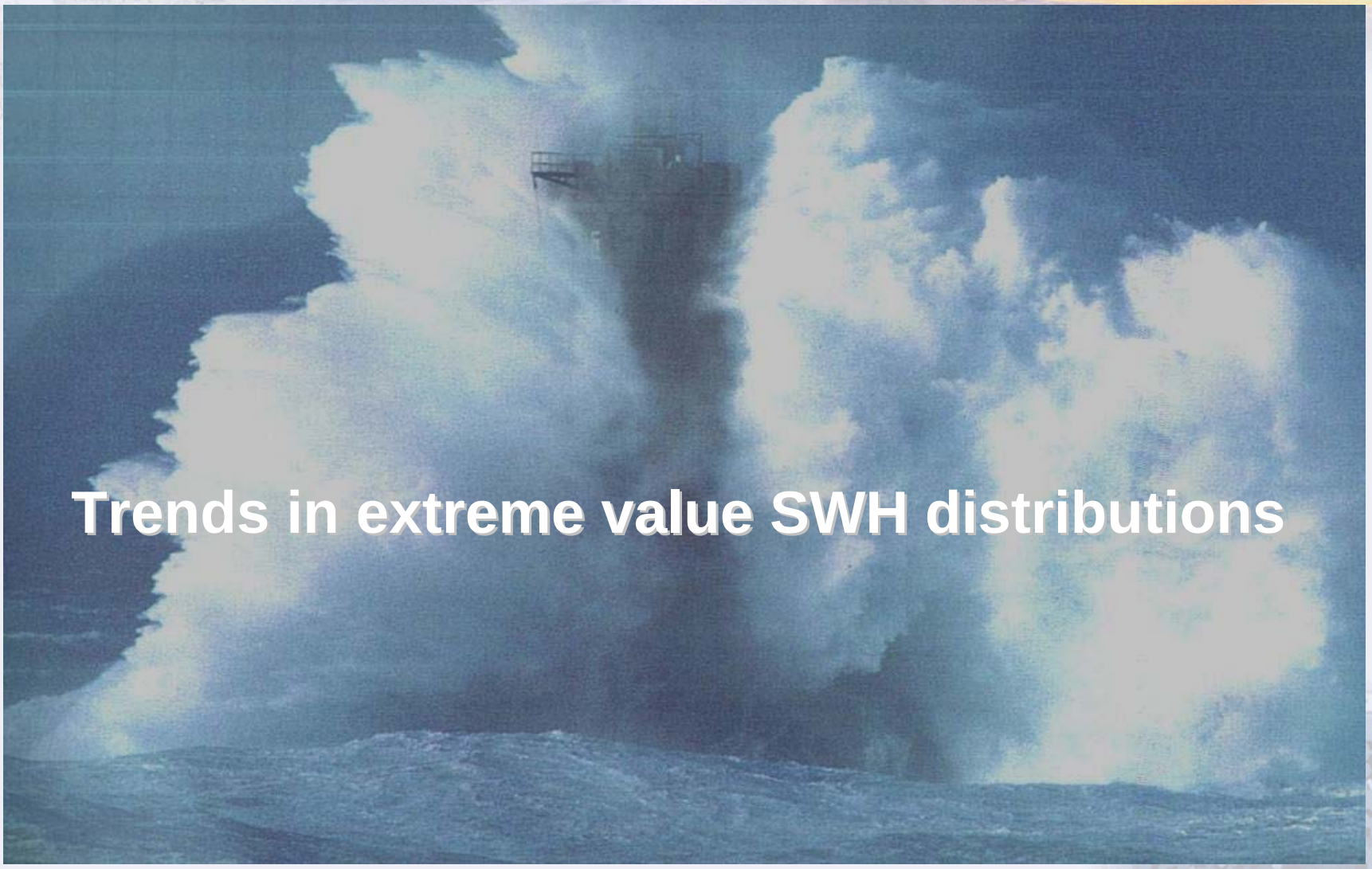

Trends in extreme value SWH distributions

Trends in extreme value pdfs

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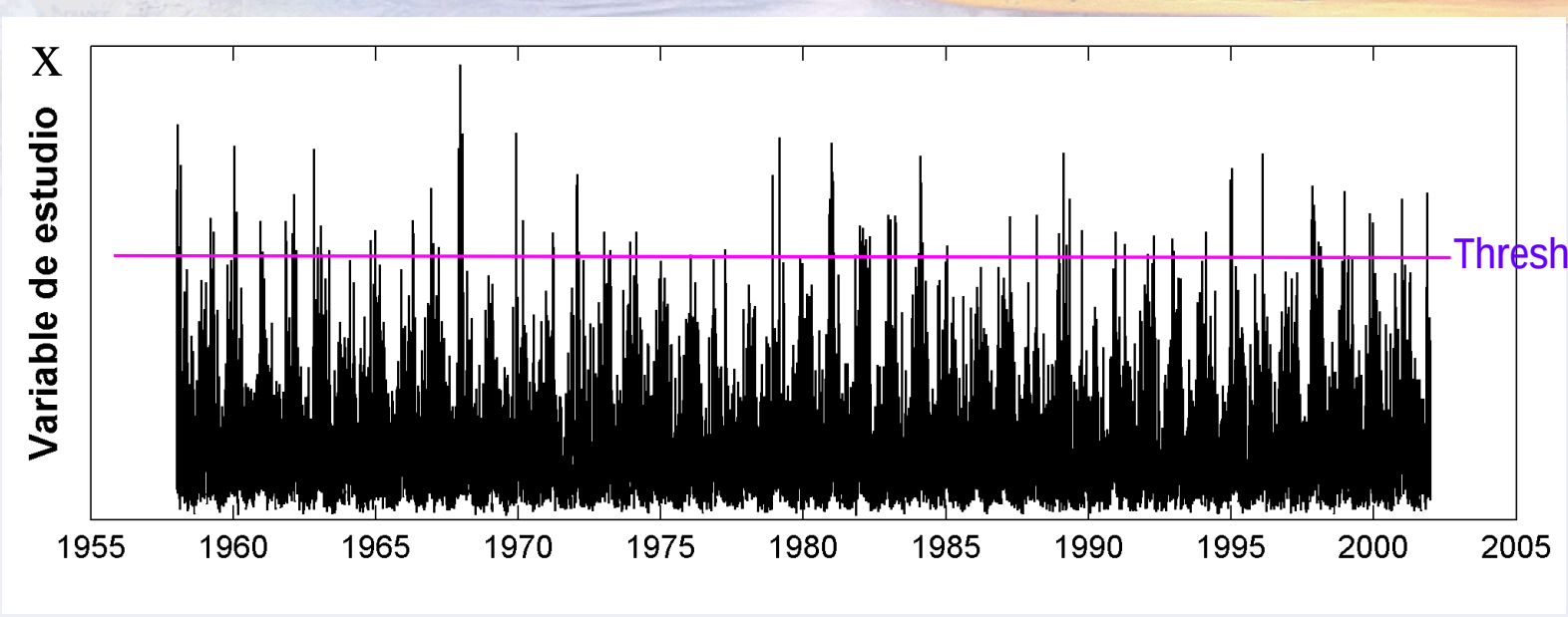
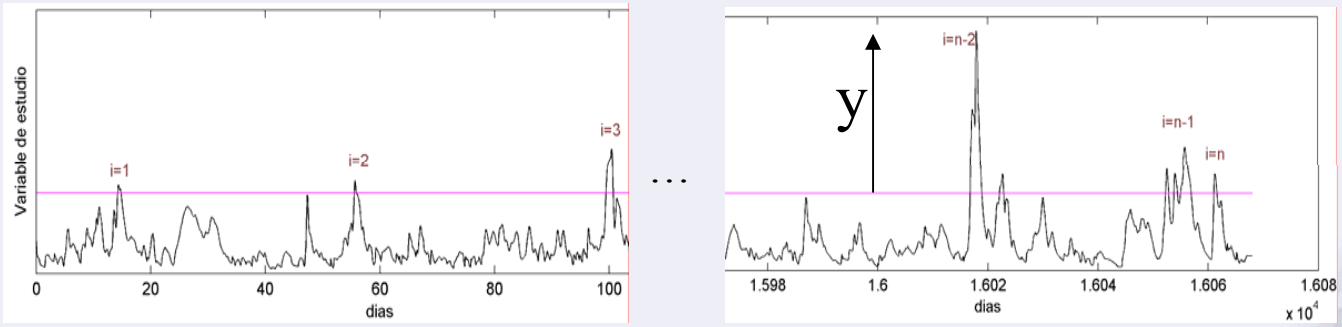
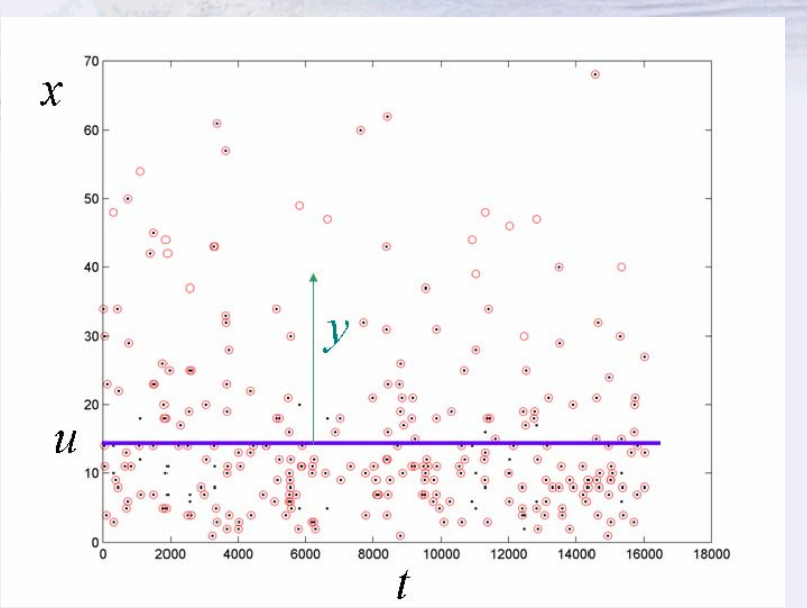




Time series: $\{(y_1,t_1,)(y_2,t_2),\ldots,(y_{N-1},t_{N-1}),(y_N,t_N)\}$



Generalized Pareto Distribution – Poisson (**GPD–P**)

$y_1, y_2, \ldots, y_N$ independent exceedances in T years

Frequency: the number of exceedances in a year over the threshold u is Poisson distributed with mean ν

$$P_\nu(n) = \frac{\nu^n e^{-\nu}}{n!}$$

Intensity: The exceedances $y_1, y_2, \ldots, y_N$ are GPD random variable

$$G(y;\sigma,\xi) = 1 - \left(1 + \xi y/\sigma\right)^{-1/\xi}$$

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Distribution GPD-P

Intensity: $G(y;\sigma,\xi) = 1-\left(1+\xi y/\sigma\right)^{-1/\xi}$ Frequency: $P_\nu(n) = \dfrac{\nu^n e^{-\nu}}{n!}$

Relationship between GPD-P and GEV (Generalized Extreme Value)

$$\Pr\left\{\max_{1\le i\le N} Y_i \le x\right\} = \Pr\{N=0\} + \sum_{n=1}^{\infty}\Pr\{N=n, Y_1\le x,\ldots Y_n\le x\} =$$

$$e^{-\nu} + \sum_{n=1}^{\infty}\frac{\nu^n e^{-\nu}}{n!}\left\{1-\left(1+\xi\frac{x-\mu}{\psi}\right)^{-1/\xi}\right\}^n = \exp\left\{-\nu\left(1+\xi\frac{x-\mu}{\psi}\right)^{-1/\xi}\right\}$$

GEV

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

$\mu \rightarrow location$

$\psi \rightarrow scale$

$\xi \rightarrow shape$

$$\sigma = \psi + \xi(u-\mu)$$

$$\nu = \left(1+\frac{\xi(u-\mu)}{\psi}\right)^{-1/\xi}$$

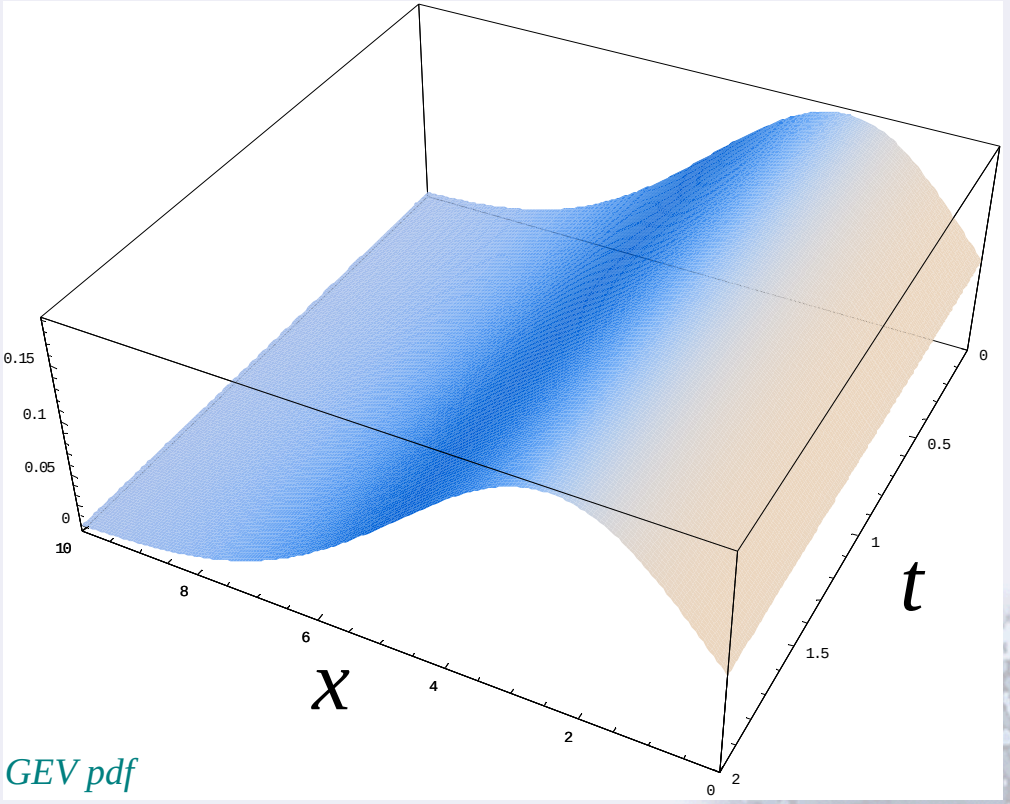
How do we calculate long-term trends ?

Stationary model

$$\mu = \mu_0$$

$$\psi = \psi_0$$

$$\xi = \xi_0$$

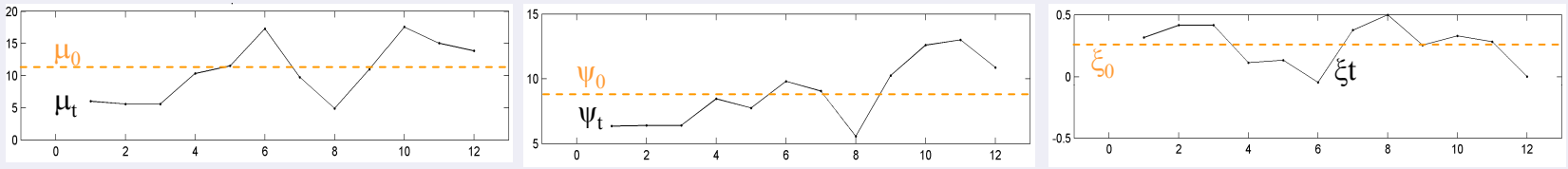


GEV pdf

How do we calculate long-term trends ?

Non-stationary model: modeling the different time scales involved

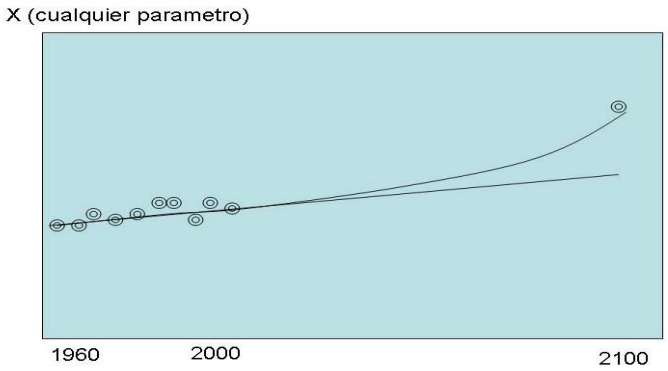
- Seasonality



$$\beta_0 + \sum_{i=1}^{P} \left[\beta_{2i-1} \cos(ikt) + \beta_{2i} \sin(ikt) \right]$$

- Trends

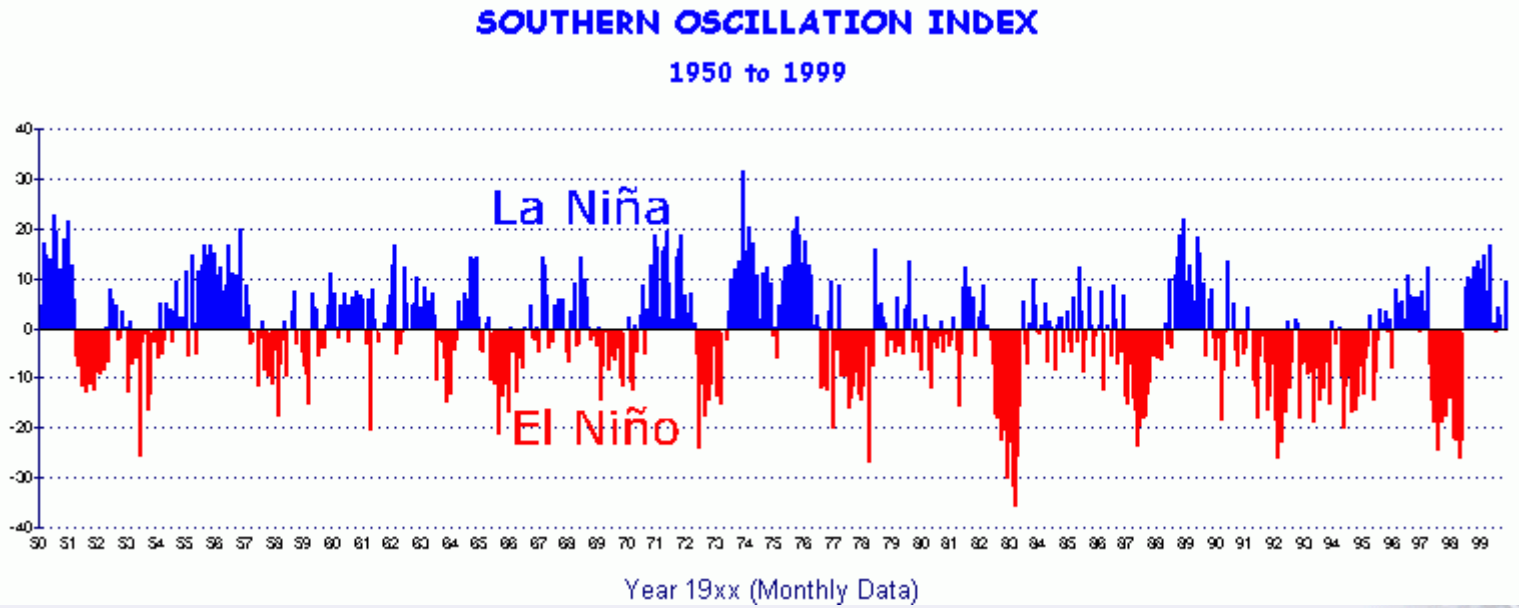
$$\beta = \beta_0 \cdot e^{\beta_5 t} \approx \beta_0 \cdot (1 + \beta_5 t)$$



How do we calculate long-term trends ?

Non-stationary model: modeling the different time scales involved

- Interdecadal variability



$$\beta_{SOI} SOI(t)$$

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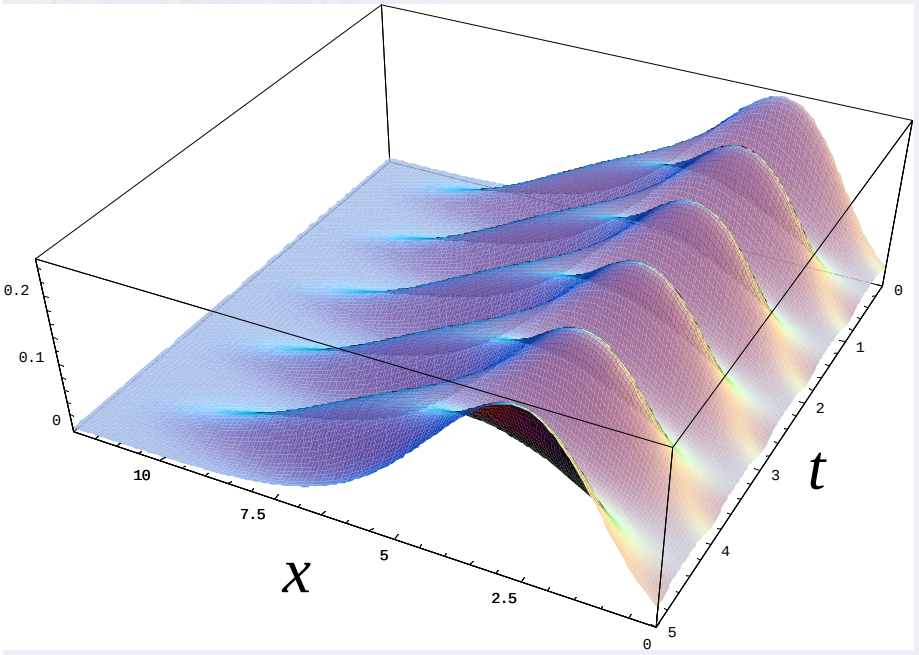
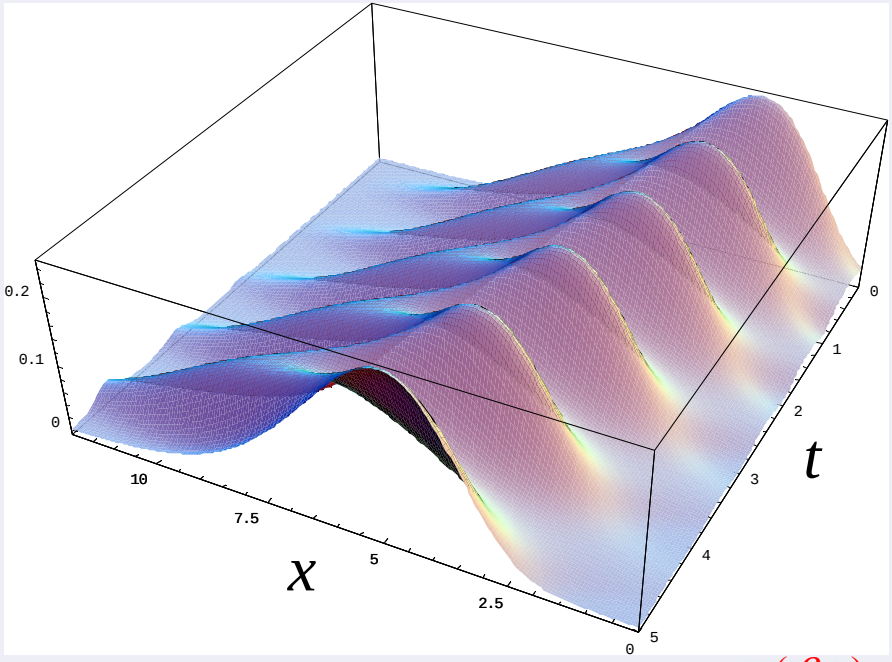
How do we calculate long-term trends ?

Non-stationary model: we consider seasonality and a long-term trend





$$\mu_t = \left[\beta_0 + \beta_1 \cos(2\pi t) + \beta_2 \sin(2\pi t) + \beta_3 \cos(4\pi t) + \beta_4 \sin(4\pi t)\right] e^{(\beta_5 t)}$$

$$\psi_t = \psi_0$$

$$\xi = \xi_0$$

Coles (2001), Smith(2001), Katz et al., (2002)

Maximum likelihood method

$$\theta = (\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \psi_0, \xi_0)$$ *Parameter vector*

$$\ell_{y,t}(\theta) = \sum_{t(days)} \left\{ \eta_{t_i} \log \nu(t_i) - \frac{\nu(t_i)}{365.25} - \eta_{t_i} \log \sigma(t_i) - \eta_{t_i} \left(1 + \frac{1}{\xi}\right) \log\left(1 + \xi \frac{y_i}{\sigma(t_i)}\right) \right\}$$

⇓ *Maximization of the log-likelihood function*

$$\hat{\theta} = (\hat{\beta}_0, \hat{\beta}_1, \hat{\beta}_2, \hat{\beta}_3, \hat{\beta}_4, \hat{\beta}_5, \hat{\psi}_0, \hat{\xi}_0)$$

Trends in extreme value pdfs

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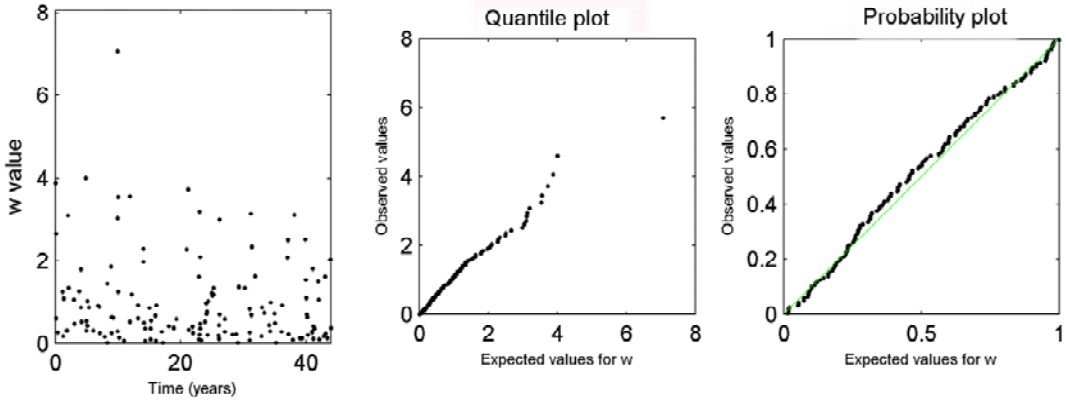
W statistic → check intensities

Z statistic → check frequencies



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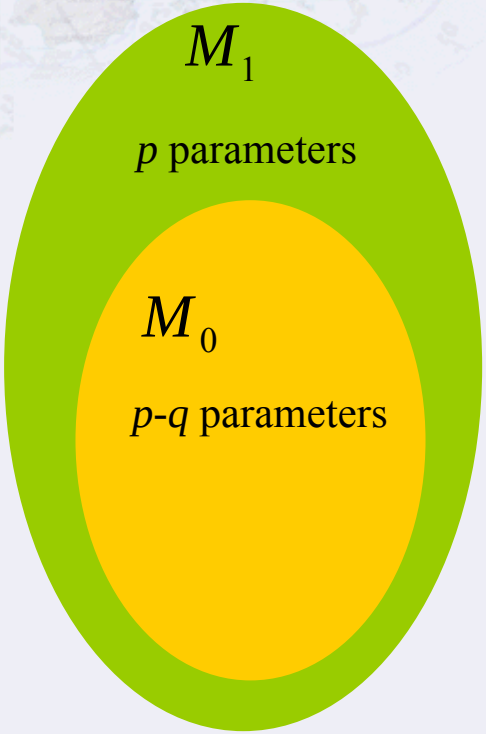


A number of models: different combinations of the extreme value parameters as functions of time and other covariates.

Objective: obtain the simplest possible model (following the principle of parsimony) that fits the data sufficiently well.

Model selection is performed using the likelihood ratio test. With nested models

$$\left[\ell_1(M_1) - \ell_0(M_0)\right] > \frac{1}{2}\chi^2_{k,1-\alpha}$$

M_1 is better than M_0 at the α-level of significance: explain more variability in the data

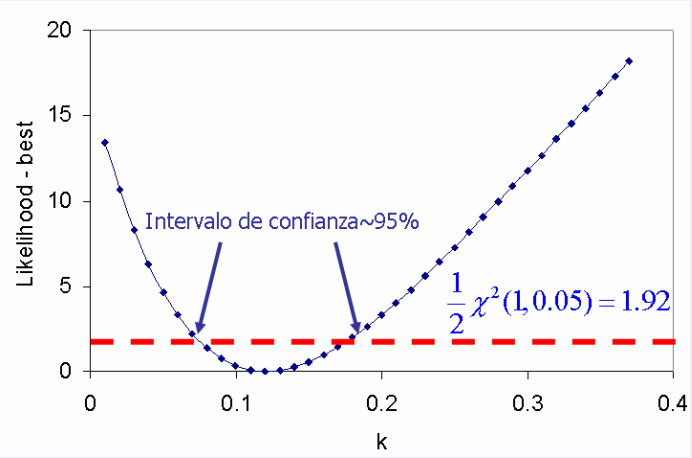
5. Determination of quantiles

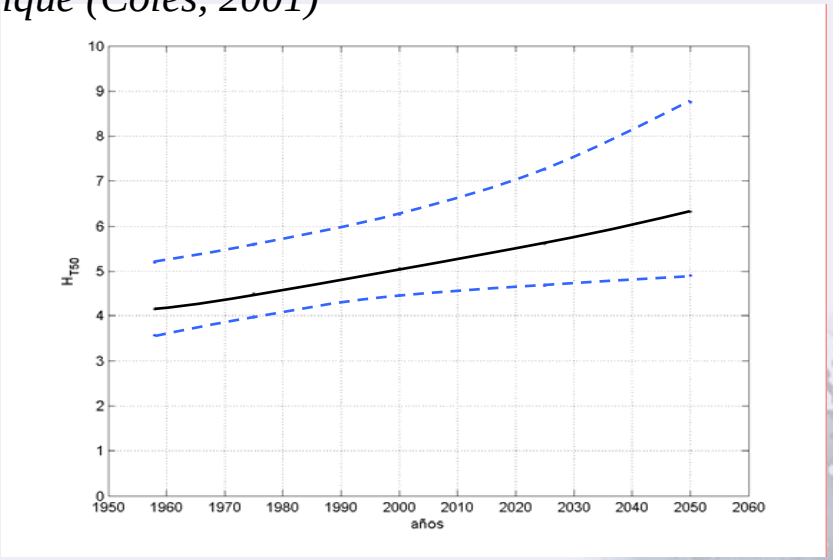
From the GEV:

$$\begin{cases} Y_N = \mu_t + \dfrac{\psi_t}{\xi_0}\left[1-\left\{-\log\left(1-\dfrac{1}{N}\right)\right\}^{-\xi_0}\right] & (\xi_0 \neq 0) \\ Y_N = \mu_t - \psi_t \cdot \log\left\{-\log\left(1-\dfrac{1}{N}\right)\right\} & (\xi_0 = 0) \end{cases}$$

6. Confidence intervals

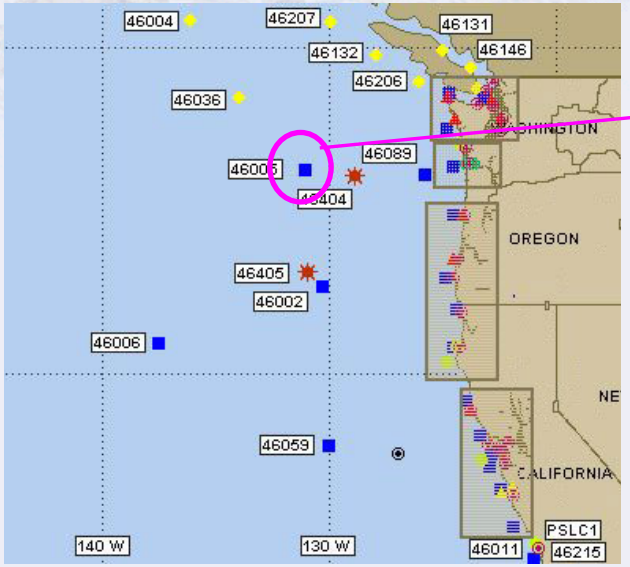
Delta method and profile likelihood technique (Coles, 2001)

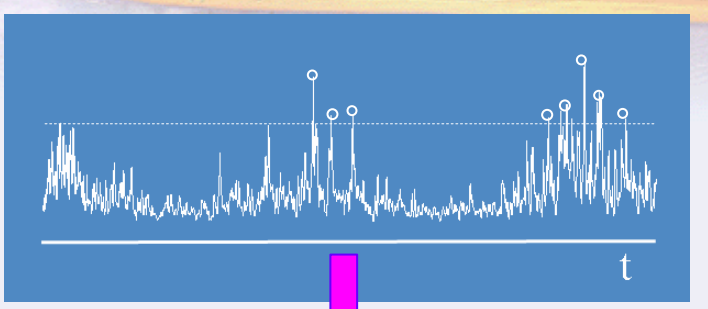




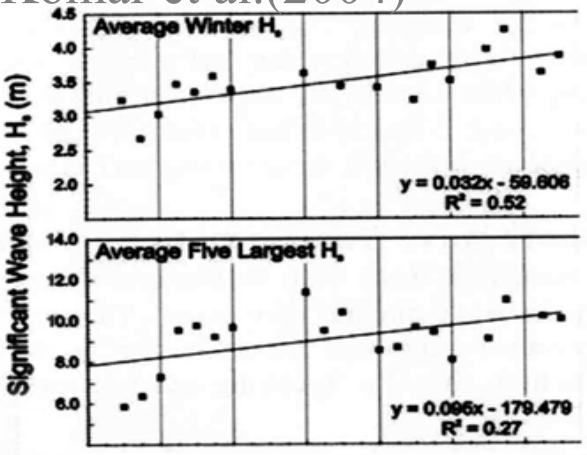
WAVE CLIMATE VARIABILITY

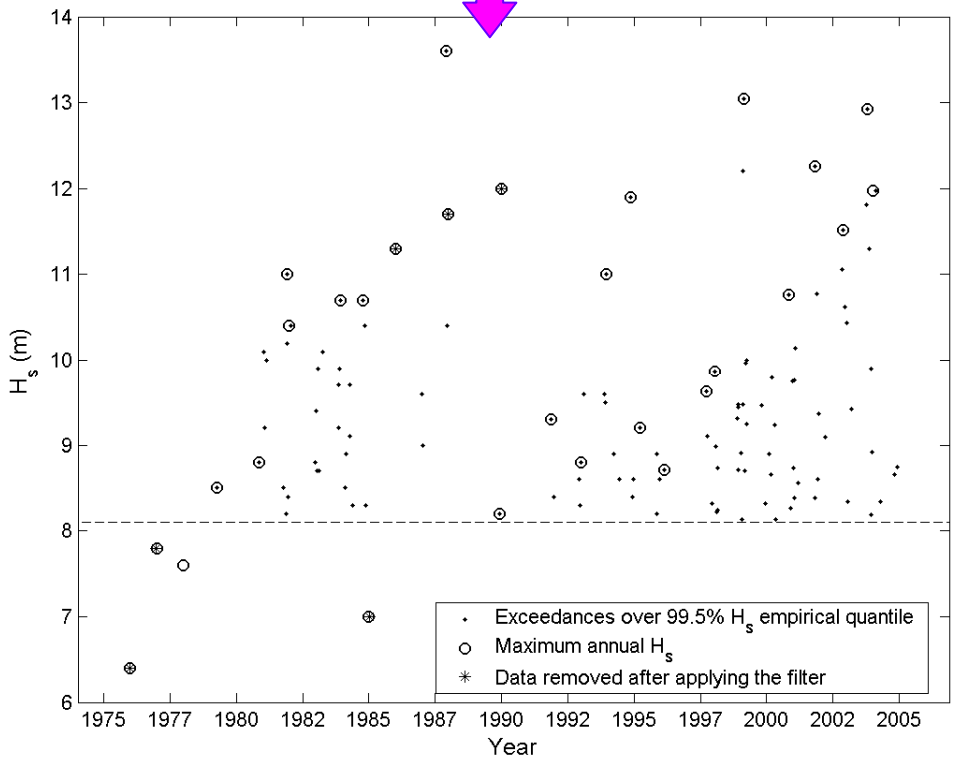
Trends in extreme value pdfs





Komar et al.(2004)





WAVE CLIMATE VARIABILITY

Trends in extreme value pdfs

ML estimate	GEV0	GEV-1	GPD-P0	GPD-P1	GPD-P2	GPD-P3	GPD-P4
$\hat{\psi}_0$	157,6126	124,6533	124,8138	122,6696	109,4929	108,1536	102,9884
$\hat{\xi}_0$	-0,2593	-0,0876	-0,1918	-0,1885	-0,1995	-0,2094	-0,2471
$\hat{\beta}_0$	985,5673	846,5659	1012,7756	895,2973	788,0334	834,9193	756,2395
$\hat{\beta}_1$	-	-	-	-	37,2036	39,0332	26,8515
$\hat{\beta}_2$	-	-	-	-	263,3900	276,1555	255,5165
$\hat{\beta}_3$	-			-	-68,8029	-72,6072	-67,2650
$\hat{\beta}_4$	-	-	-	-	-52,2007	-53,1919	-48,8181
$\hat{\beta}_5$	-	0,0106	-	0,0080	0,0076	-0,0034	0,0089
$\hat{\beta}_6$	-	-	-	-	-	0,0004	-
$\hat{\beta}_{SOI}$	-	-	-	-	-	-	-42,9024
ℓ	-149,5461	-146,29	-609,6133	-600,9391	-543,325	-542,298	-539,7714

Trends in extreme value pdfs

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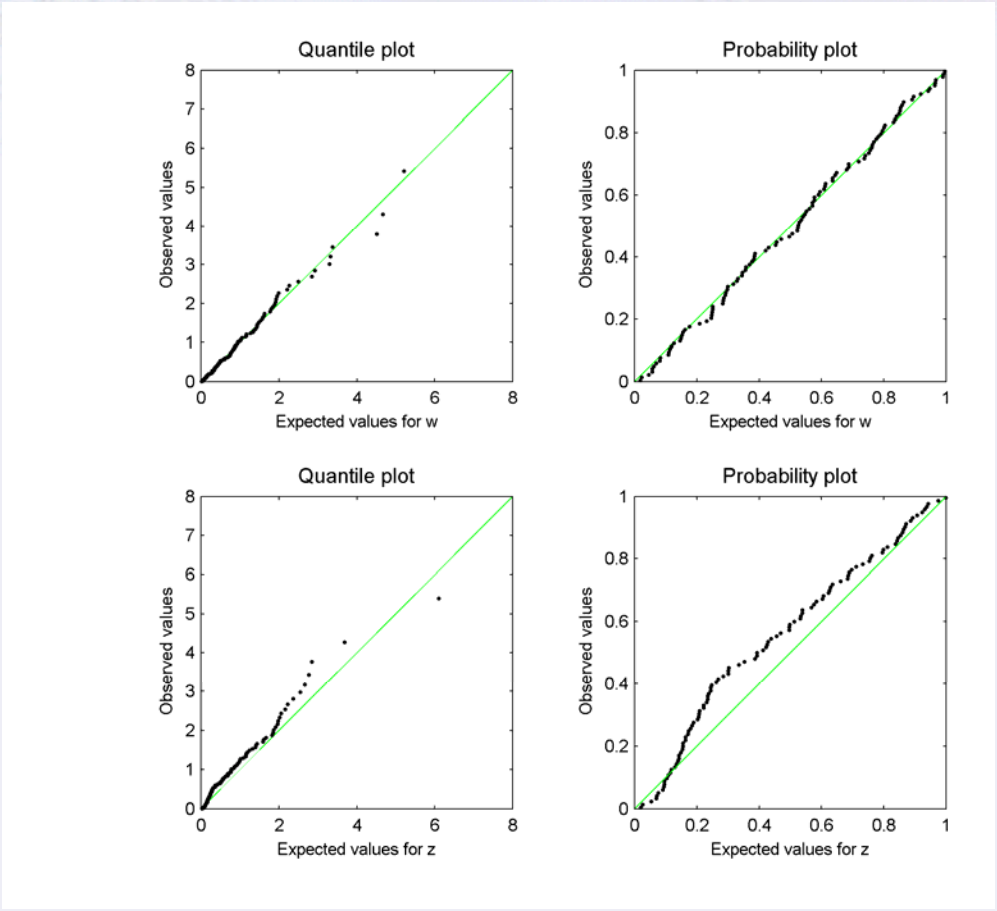

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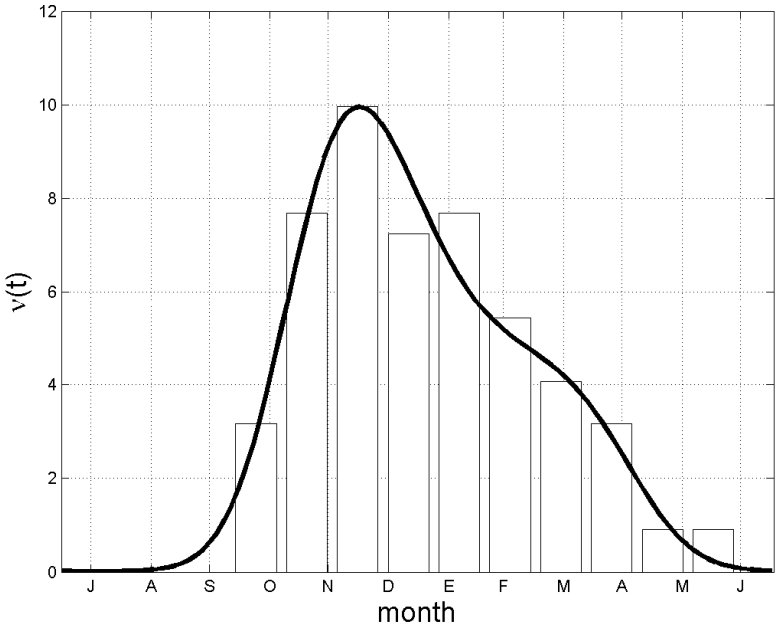
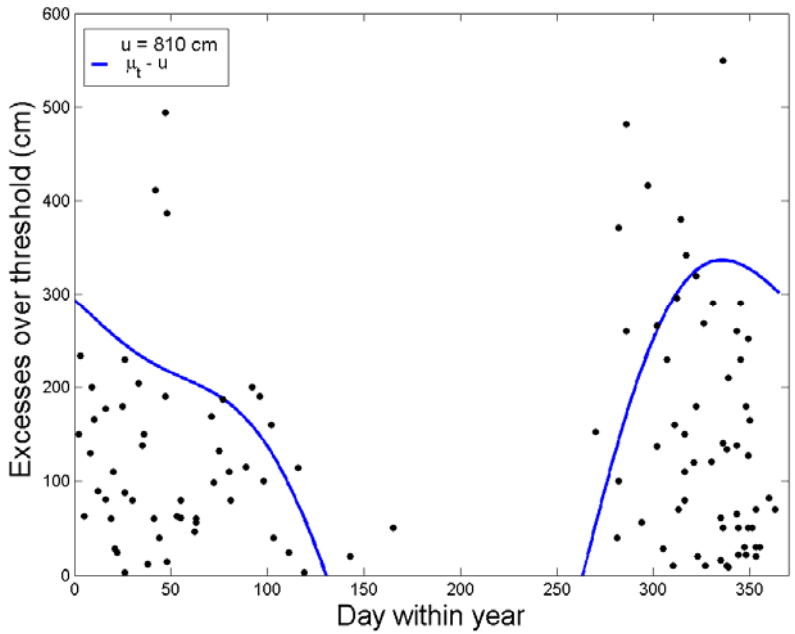
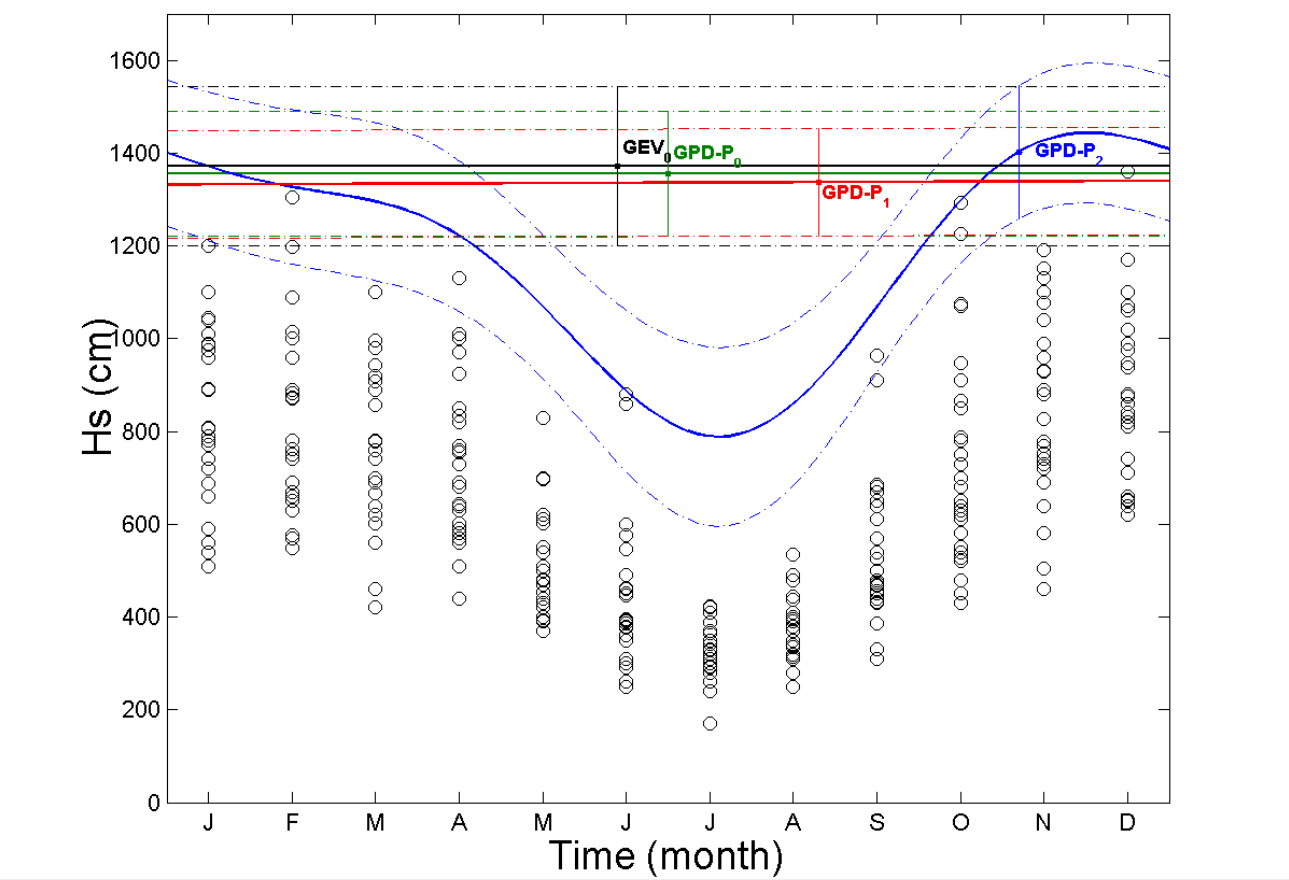
Frequency



Intensity



$H_{N=50\ years}$


1600
1400
1200
1000
800
600
400
200
0
Hs (cm)
GEV0
GPD-P0
GPD-P1
GPD-P2
J
F
M
A
M
J
J
A
S
O
N
D
Time (month)

Trends in extreme value pdfs

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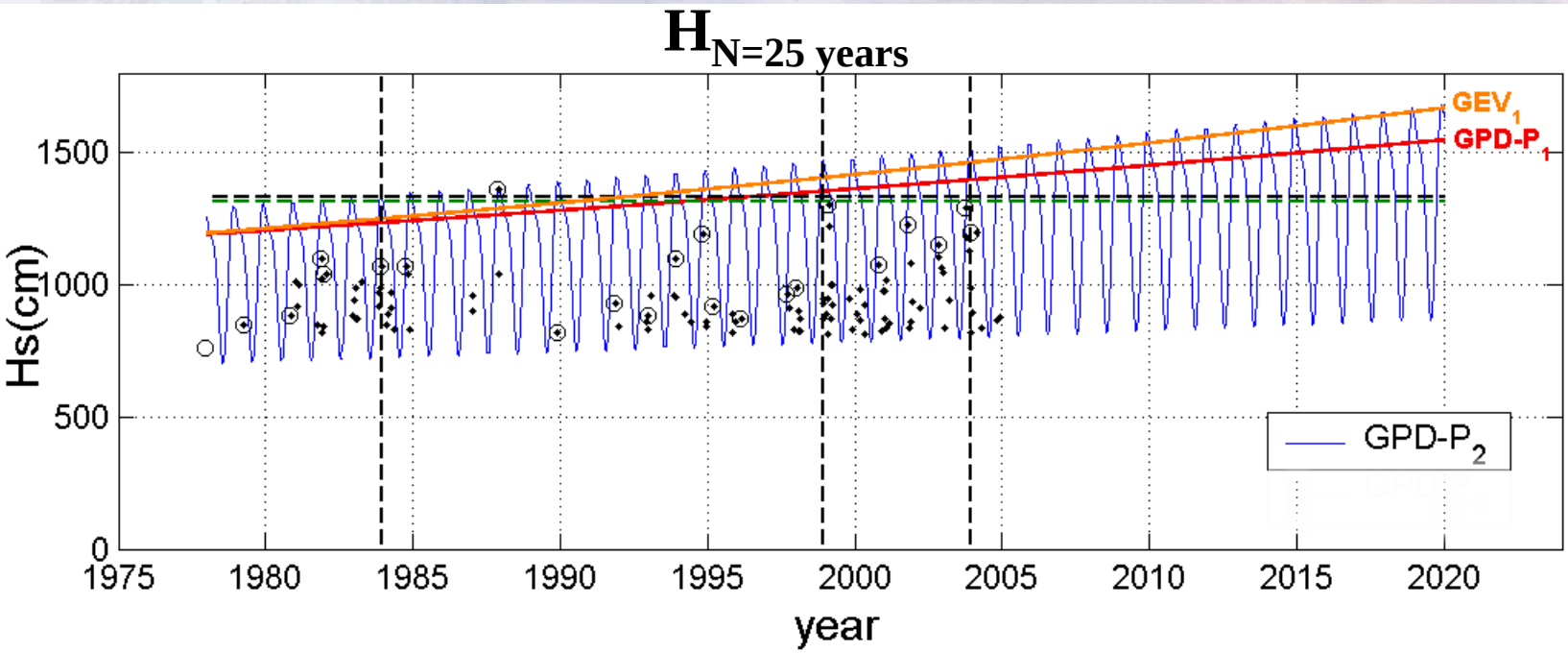

GEV$_1$	$\hat{\beta}_0\hat{\beta}_5 = 8.5cm/yr$	
GPD-P$_1$	$\hat{\beta}_0\hat{\beta}_5 = 7.2cm/yr$	$> 99.5\%significant$
GPD-P$_2$	$\hat{\beta}_0\hat{\beta}_5 = 6.0cm/yr$	$> 99.9\%significant$

Trends in extreme value pdfs

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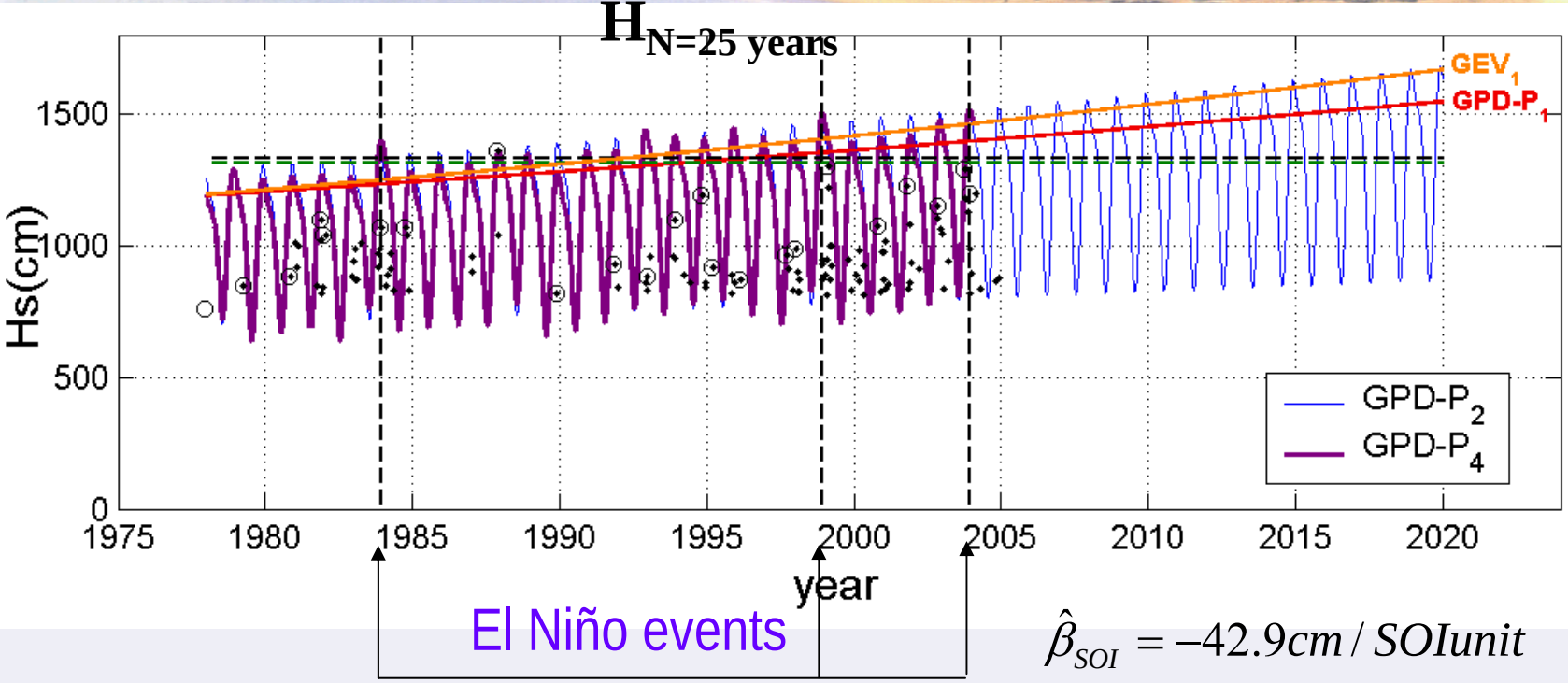

El Niño events

$$\hat{\beta}_{SOI} = -42.9cm / SOIunit$$

GEV$_1$	$\hat{\beta}_0\hat{\beta}_5 = 8.5cm/yr$	
GPD-P$_1$	$\hat{\beta}_0\hat{\beta}_5 = 7.2cm/yr$	
GPD-P$_2$	$\hat{\beta}_0\hat{\beta}_5 = 6.0cm/yr$	
GPD-P$_4$	$\hat{\beta}_0\hat{\beta}_5 = 6.7cm/yr$	$> 99\%significant$

WAVE CLIMATE VARIABILITY

Trends in extreme value pdfs

A model based on a non-stationary version of the Peak Over Threshold (POT) is developed to estimate long-term trends in the frequency and intensity of severe storm waves

The inclusion of physical processes, such as the seasonal effects, the decadal climate variability and a long-term trend provides a better explanation of the variability of the data improving the goodness of fit of the model and the significance of the parameters involved, especially the long-term trend.

This is due to: a) the POT model makes use of a considerable higher number of major storms, rather than using annual maxima; b) the seasonal-to-decadal physical processes included in the model reduce the “noise” in the determination of the long-term trend.

Trends in extreme value pdfs

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For the particular data set analized (Washington buoy, #46005), the more complex the model, the smaller the long-term positive trend. Nevertheless, the inclusion of SOI as a covariate does not affect the long-term trend estimation.

Results show that the model is appropriate for a strict analysis of long-term trends and climate variability of extreme waves providing time dependent quantiles and confidence intervals.

Outline

1. Motivation
2. Spatial calibration
3. Time scales of wave climate variability
4. Trends in long-term distributions
    1. Scalar variables
    2. Directional variables
5. Trends in long-term extreme value distributions
6. Effects of climate change on the spanish coast

WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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IC3

"Effects of the climate change on the spanish coast"(2002-2004)

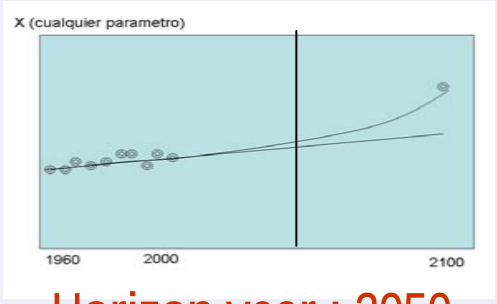
Funded by the Spanish Agency of Climate Change
(Ministerio de Medio Ambiente, SPAIN)

MINISTERIO DE MEDIO AMBIENTE

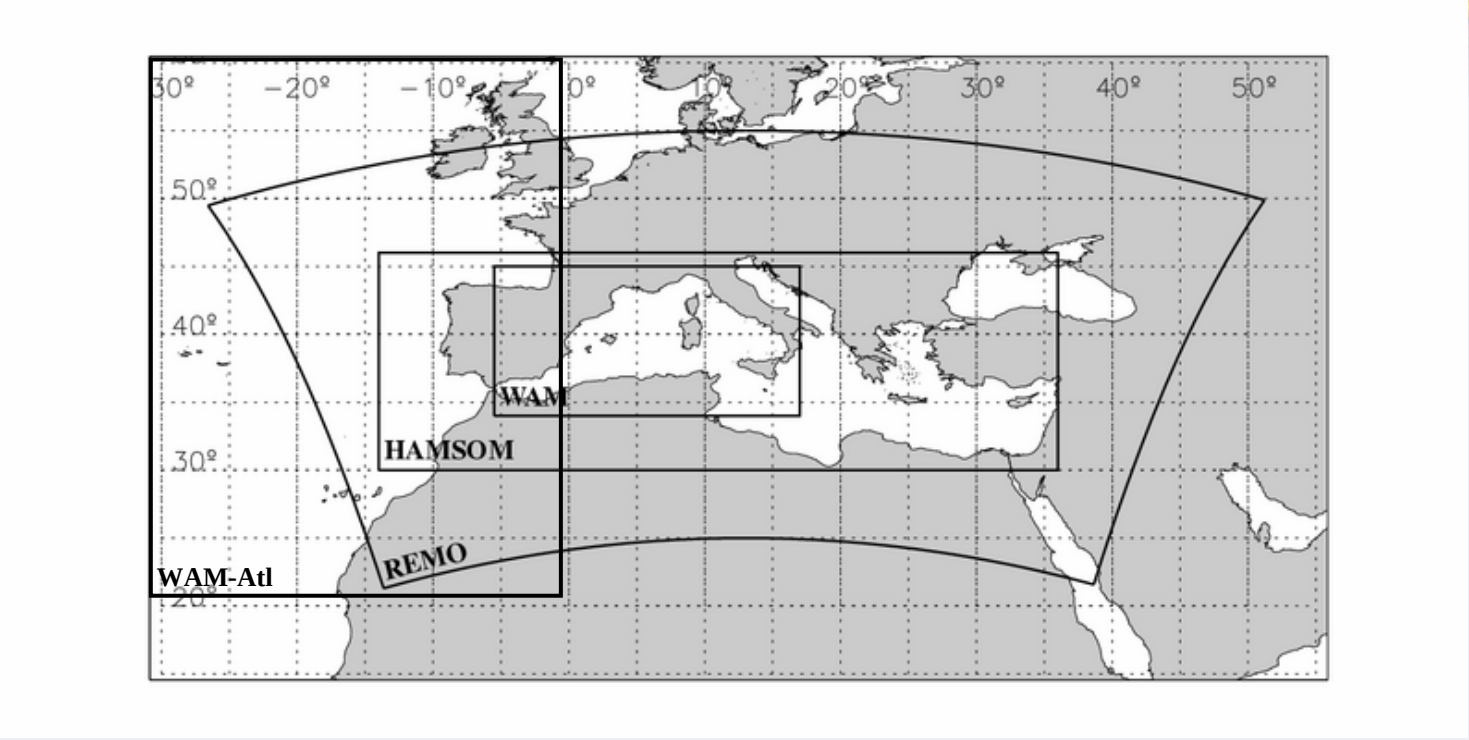
Phase I: To evaluate wave climate and sea level changes along the littoral

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Phase III: To establish strategies



Horizon year : 2050



HIPOCAS (Med) + AR (Atl): Hindcast model (1958-2001) *EPPE(2003)*

REMO: W_c

HAMSOM: MM_c

WAM: Hs_c (*Tomás et al, 2006*)

WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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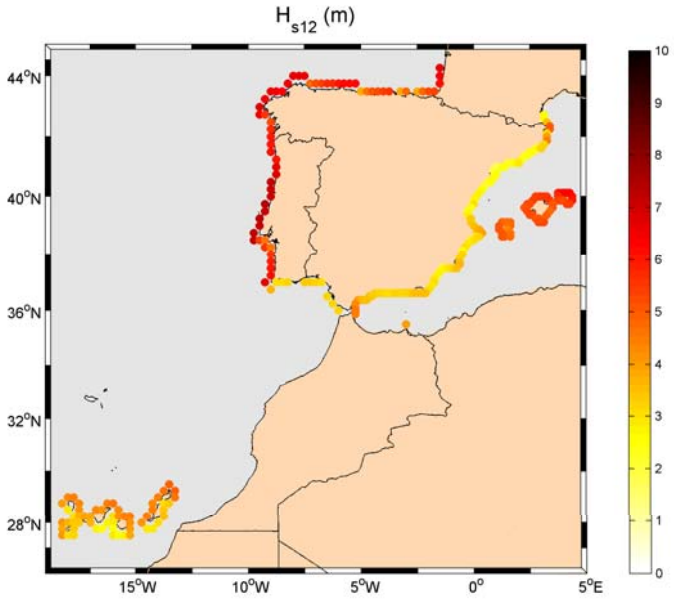
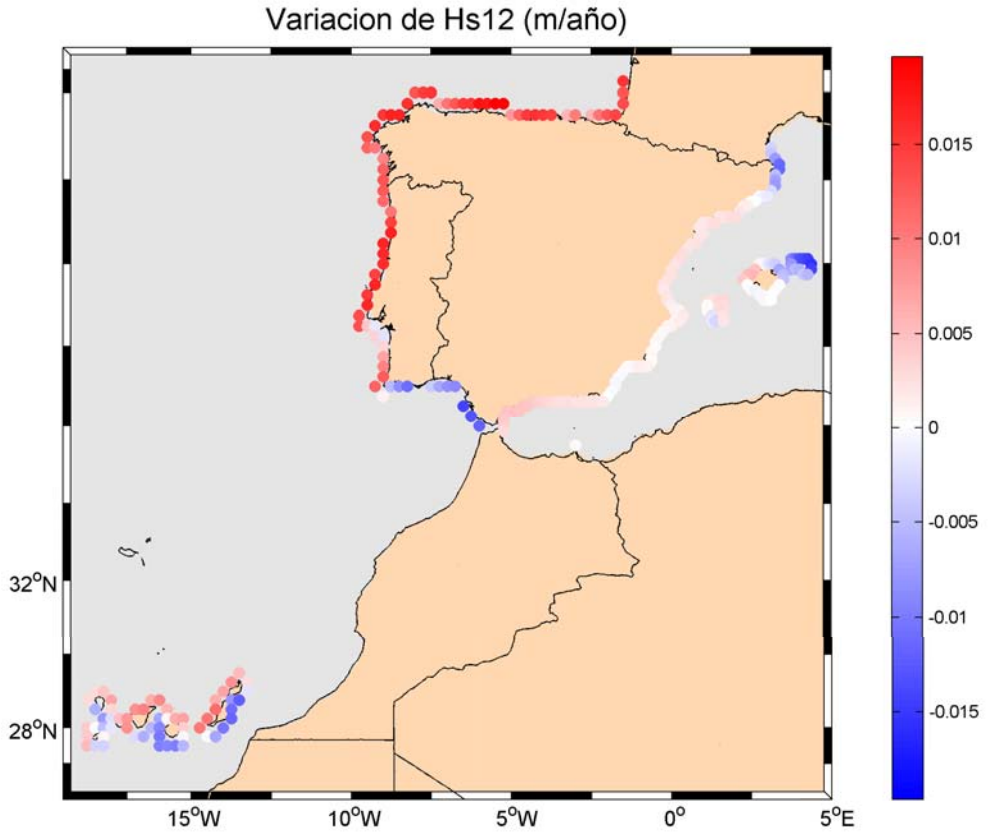
Phase I: To evaluate wave climate and sea level changes along the littoral



SWH exceeded 12 hours in a year



WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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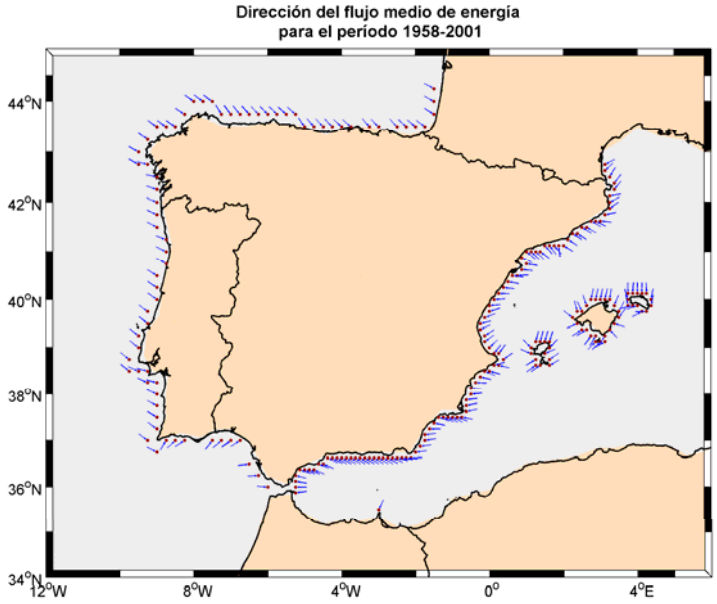
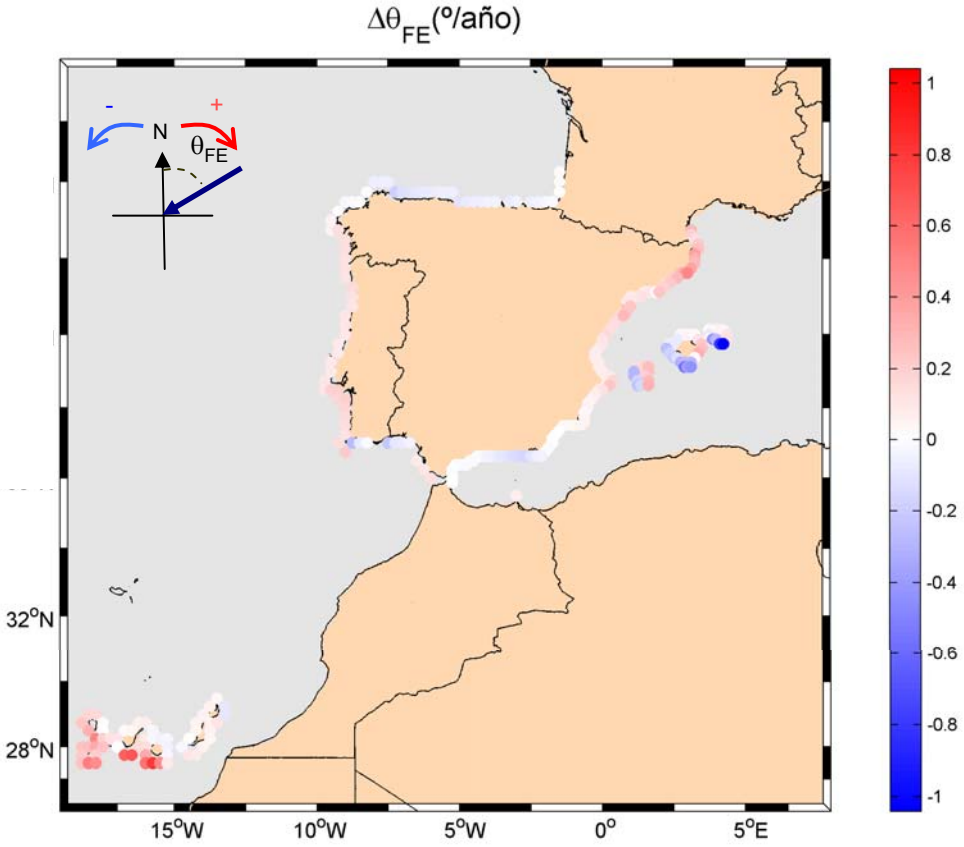
Phase I: To evaluate wave climate and sea level changes along the littoral

Direction of the mean energy flux





WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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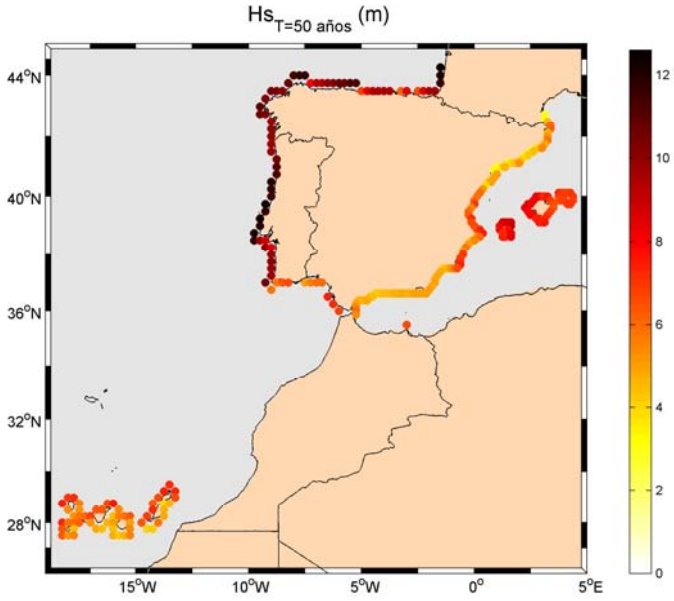
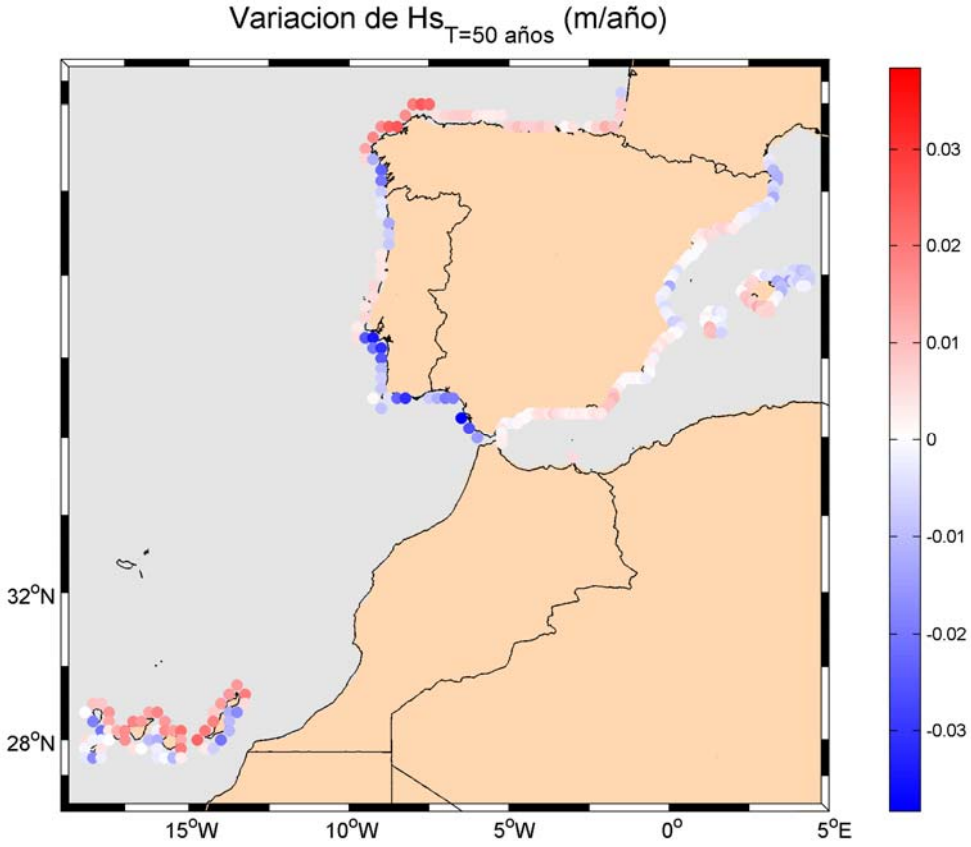
Phase I: To evaluate wave climate and sea level changes along the littoral

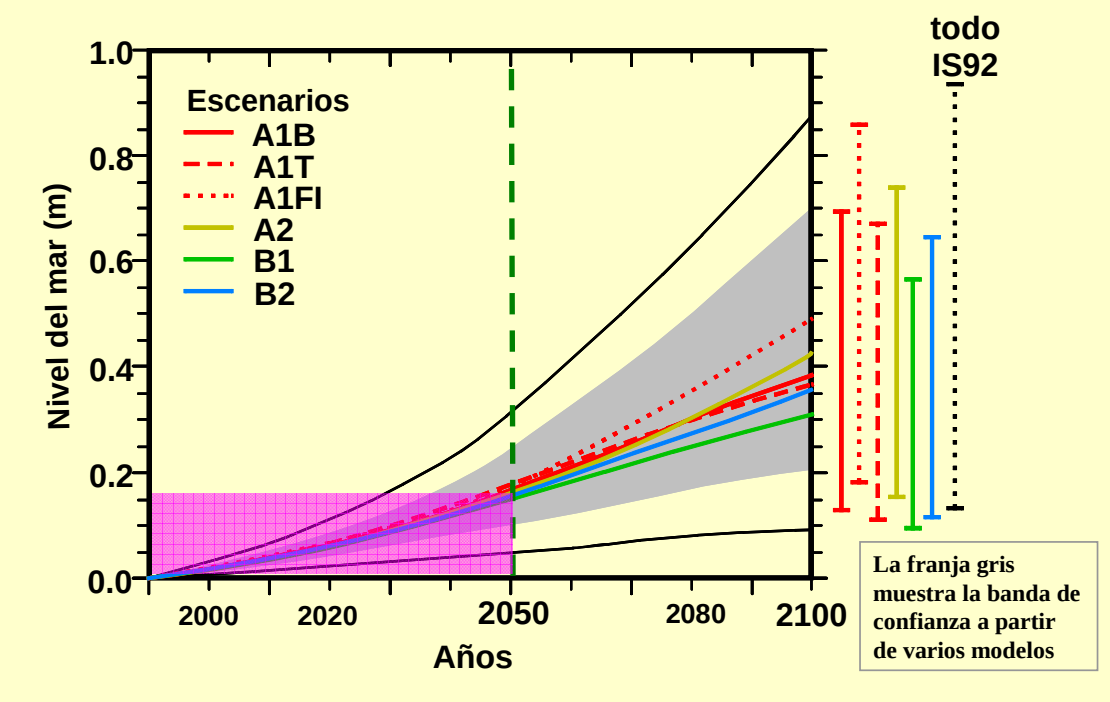


SWH exceeded once every 50 years



Phase I: To evaluate wave climate and sea level changes along the littoral

Sea level rise



WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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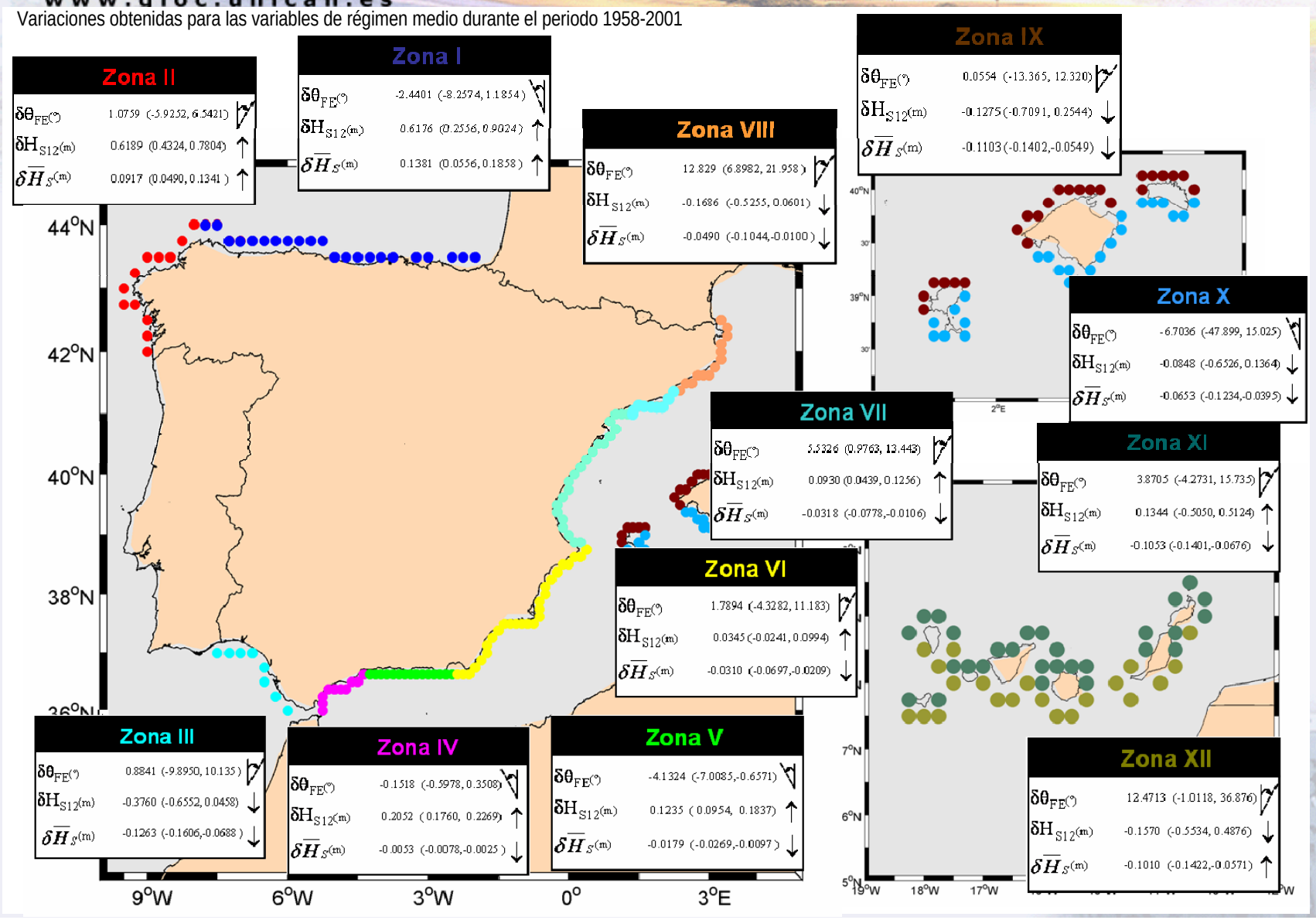
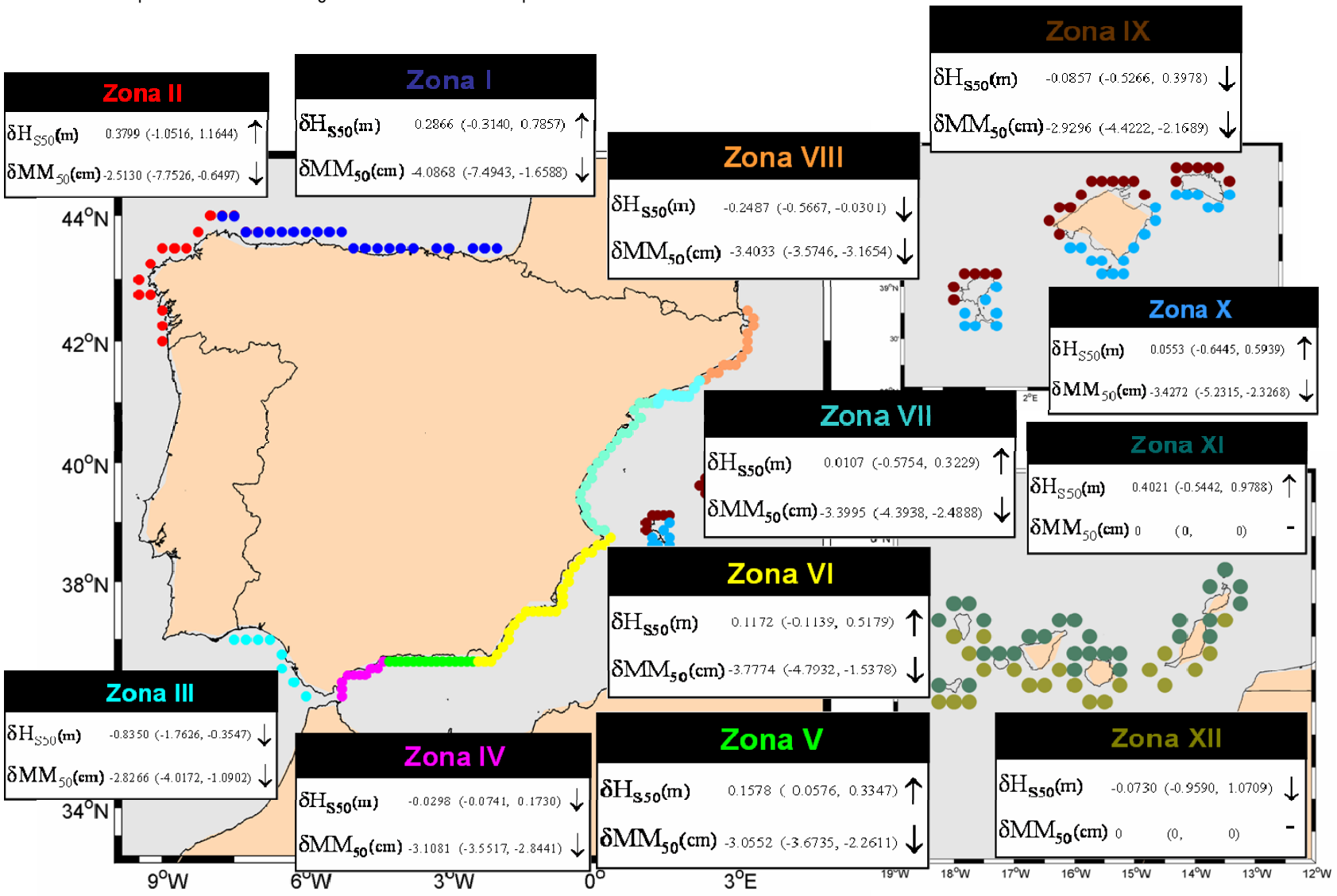
Variaciones obtenidas para las variables de régimen medio durante el periodo 1958-2001



WAVE CLIMATE VARIABILITY

Effects on the spanish coast

Variaciones obtenidas para las variables de régimen extremal durante el periodo 1958-2001



WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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"Effects of the climate change on the spanish coast"(2002-2004)

Funded by the Spanish Agency of Climate Change
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MINISTERIO DE MEDIO AMBIENTE

Phase I: To evaluate wave climate and sea level changes along the littoral

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Phase III: To establish strategies

EFECTOS PRINCIPALES EN PLAYAS:

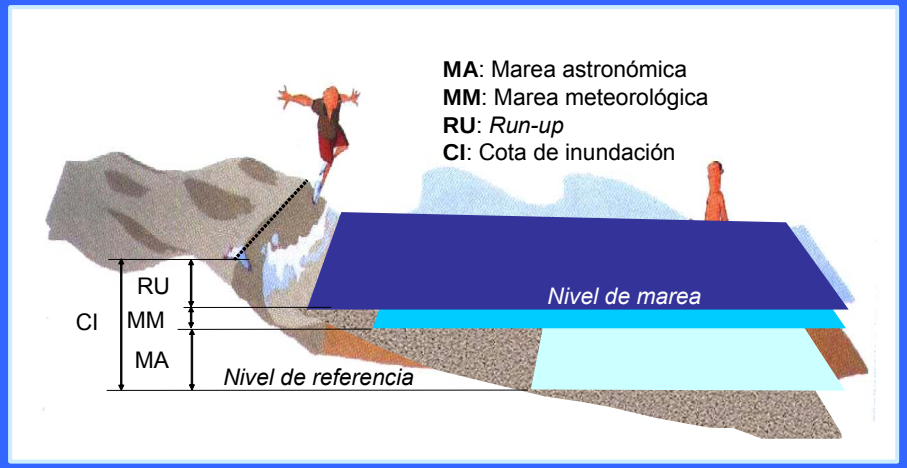
		OLEAJE				NIVEL DEL MAR	MAREA METEOROLÓGICA
		REGIMEN MEDIO			EXTREMAL		
ELEMENTO MORFOLÓGICO	**ELEMENTOS ANALIZADOS**	ΔH_{s12}	ΔH_{RMS}	$\Delta\theta$	$\Delta H_{s,T=50\ años}$	**NM**	**ΔMM**
PLAYAS	**COTA DE INUDACIÓN**				POSIBLE AUMENTO COTA DE INUNDACIÓN	POSIBLE AUMENTO COTA DE INUDACIÓN	POSIBLE AUMENTO COTA DE INUNDACIÓN
	PERFIL	AUMENTO PROFUNDIDAD DE CORTE, POSIBLE RETROCESO EN PLAYAS COLMATADAS				RETROCESO PLAYA	
	FORMA EN PLANTA			BASCULAMIENTO PLAYAS, POSIBLE RETROCESO		CAMBIO EN TÓMBOLOS, SALIENTES Y DOBLES SALIENTES	
	TRANSPORTE LITORAL		VARIACIÓN CAPACIDAD DE TRANSPORTE	VARIACIÓN CAPACIDAD DE TRANSPORTE			

VARIACIÓN DE LA COTA DE INUNDACIÓN

$$CI = MA + MM + Ru$$

PERTURBANDO

$$\frac{\delta CI}{CI} = \frac{\delta MM + \delta\eta + 0.0396\left(\frac{gT^2}{2\pi}\right)^{0.5}\frac{\delta H_s}{\sqrt{H_s}}}{MA + MM + 0.0792\left(H_s\frac{9.81T^2}{2\pi}\right)^{0.5}}$$

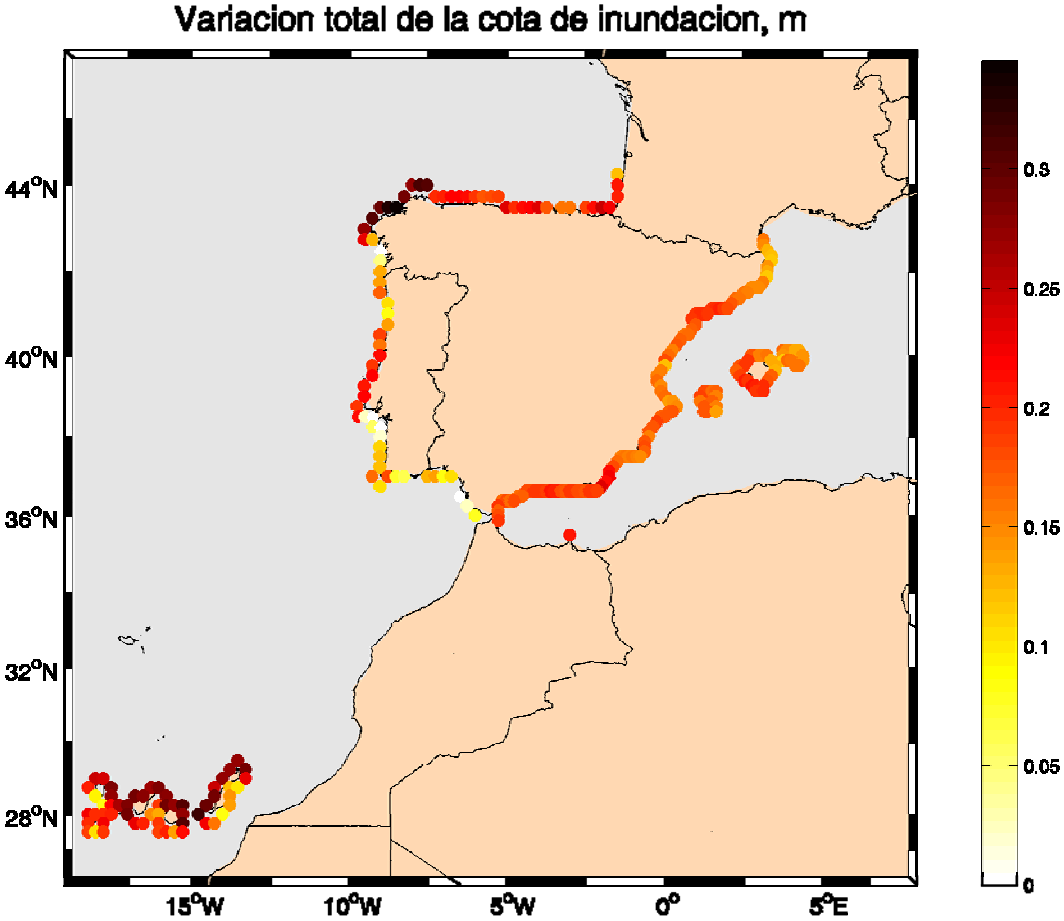


Run- up dado por Nielsen (1991) $\longrightarrow$ $$R_{u2\%} = 0.0792\left(H_s\frac{9.81T_p^2}{2\pi}\right)^{0.5}$$

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

50-year return period flooding level

DATOS REPRESENTATIVOS		
Costa Gallega e Islas Canarias	Zona Mediterránea	Golfo de Cádiz
↑ 35 cm	↑ 20 cm	↑ 10 cm



Horizon year: 2050

RETROCESO POR AUMENTO DEL NIVEL MEDIO DEL MAR

- El **ascenso del nivel del mar** produce un **ascenso del perfil de playa** sin que la forma del perfil se vea modificado.

- El ascenso debe producirse a costa de la arena existente.

- El futuro **perfil** se ve **retranqueado** para cubrir el déficit de arena.

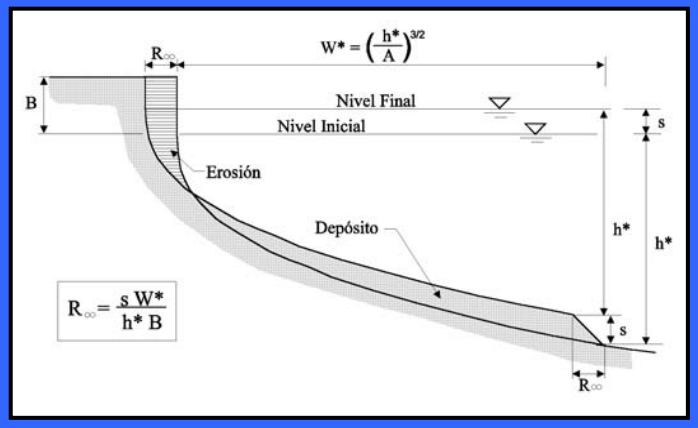
Regla de Bruun:

$$R = \Delta\eta \frac{w_*}{(h_* + B)}$$

R = Retroceso del perfil de playa
$\Delta\eta$ = Variacion del nivel medio
w_* = anchura del perfil de playa
h_* = profundidad de corte
B = altura de la berma

Dean (1987):

$$\frac{R}{\Delta\eta} = \frac{(1.57 H_{s12})^{1.5}}{(0.51 w^{0.44})^{3/2} (1.57 H_{s12} + B)}$$



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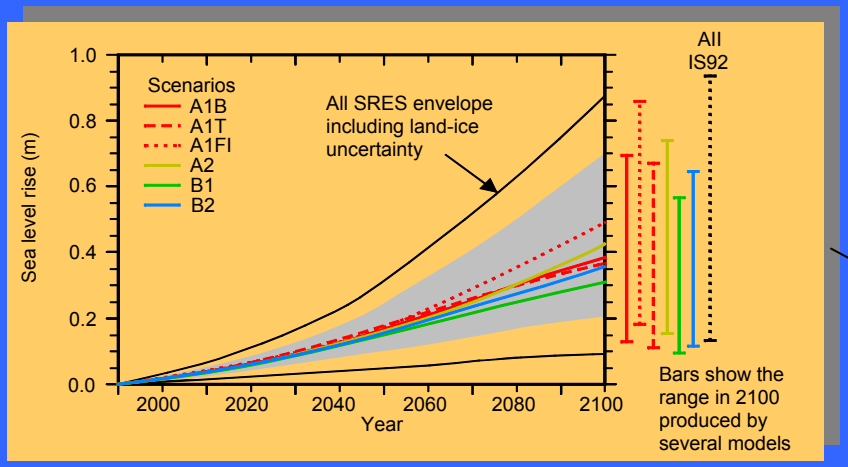
Universidad de Cantabria

Fase II: Evaluación de efectos

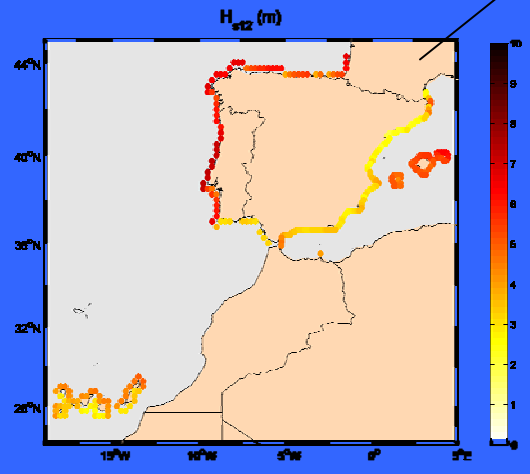
Proyecto de Investigación para el establecimiento de políticas y estrategias de actuación en la costa española por efecto del cambio climático

IPCC: Variación del nivel del mar



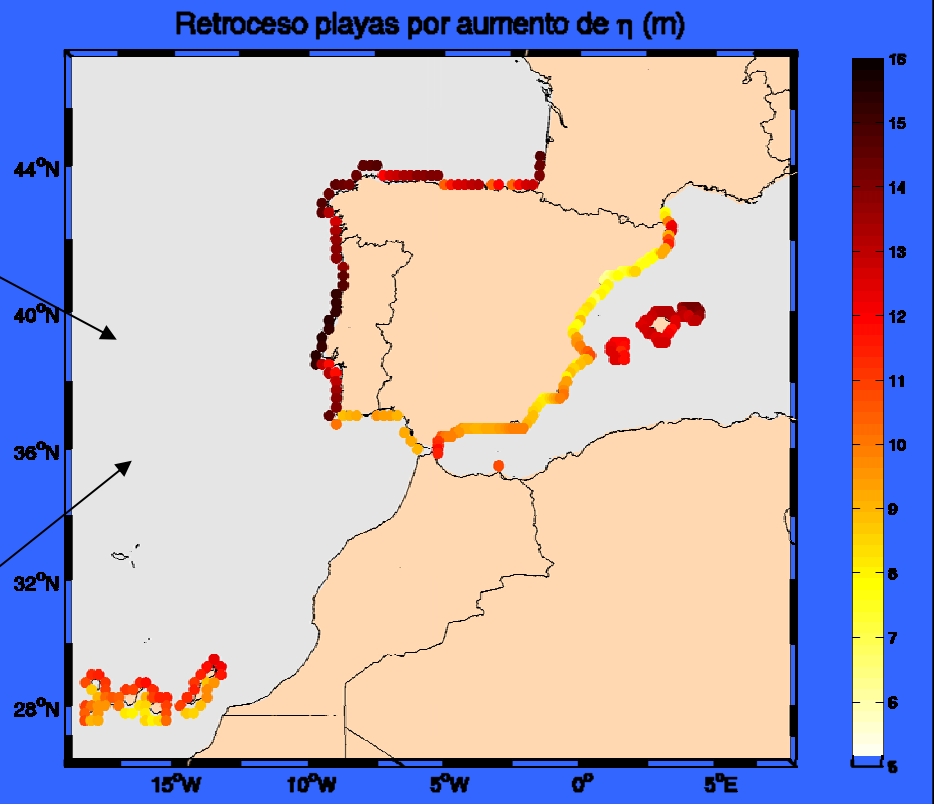
-Se ha considerado la ***tendencia media*** en el aumento del nivel medio del mar. **¡Gran incertidumbre!**

HIPOCAS



Características de la playa tipo:
-D50 0.3 mm
-B= 1 m
-Hs12: media de los valores proporcionados por el modelo HIPOCAS

Año objetivo: 2050



WAVE CLIMATE VARIABILITY

Effects on the spanish coast

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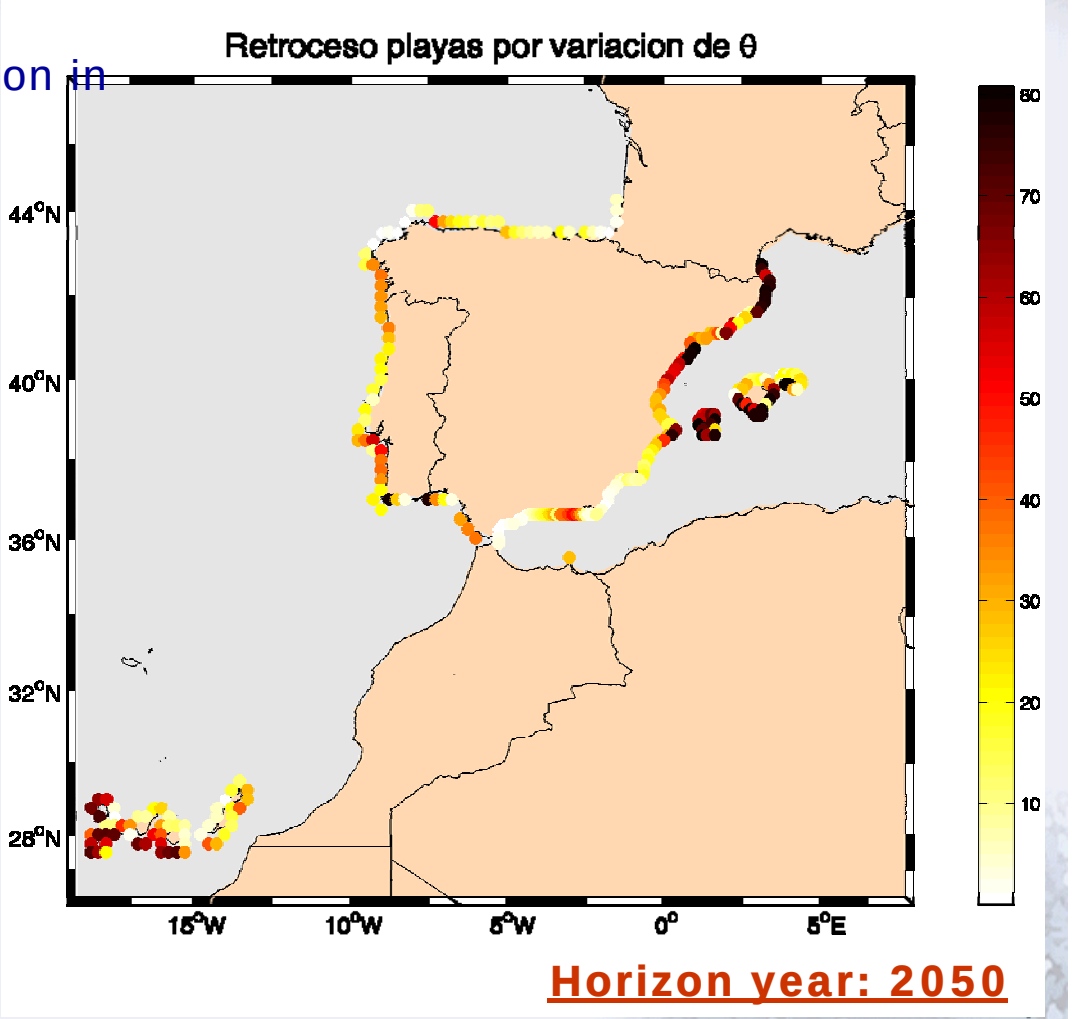
Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Planform retreat induced by the variation in the direction of the mean energy flux

1000 m longitude beaches !

Obtained in 10 m water depth using Snell's Law



Horizon year: 2050

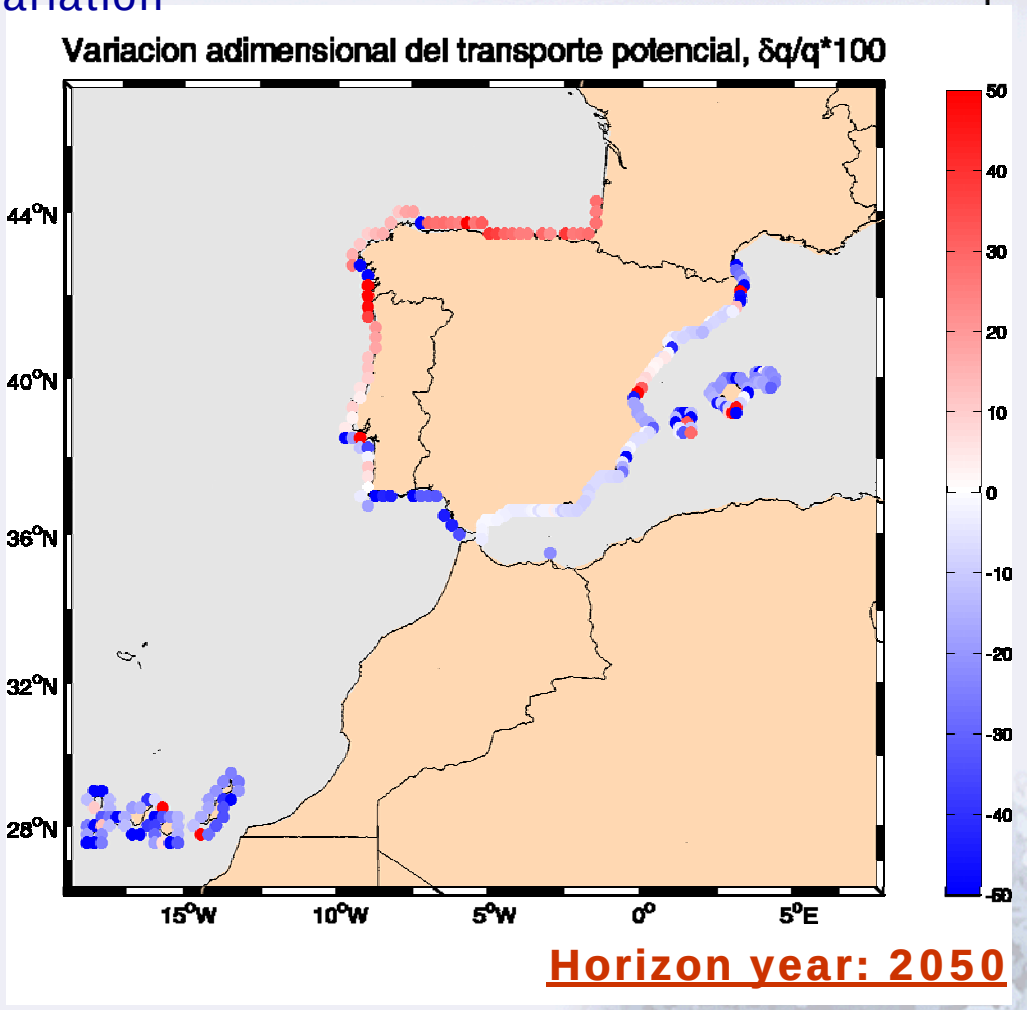
DATOS REPRESENTATIVOS		
Costa Brava, Sur de las Islas Baleares y Canarias	**Norte de Galicia y Sur Mediterráneo**	**Resto costa**
RE_{max}= 70 m	RE_{max} = 10 m	RE_{max} = 20 m

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Longshore littoral sediment transport variation

Obtained using Snell's Law

DATOS REPRESENTATIVOS		
Costa Gallega, Costa Cantábrica	**Costa Mediterránea**	**Golfo de Cádiz y Mar de Alborán**
↑ 40 %	**↓ 20-10 %**	**↓ 40 %**



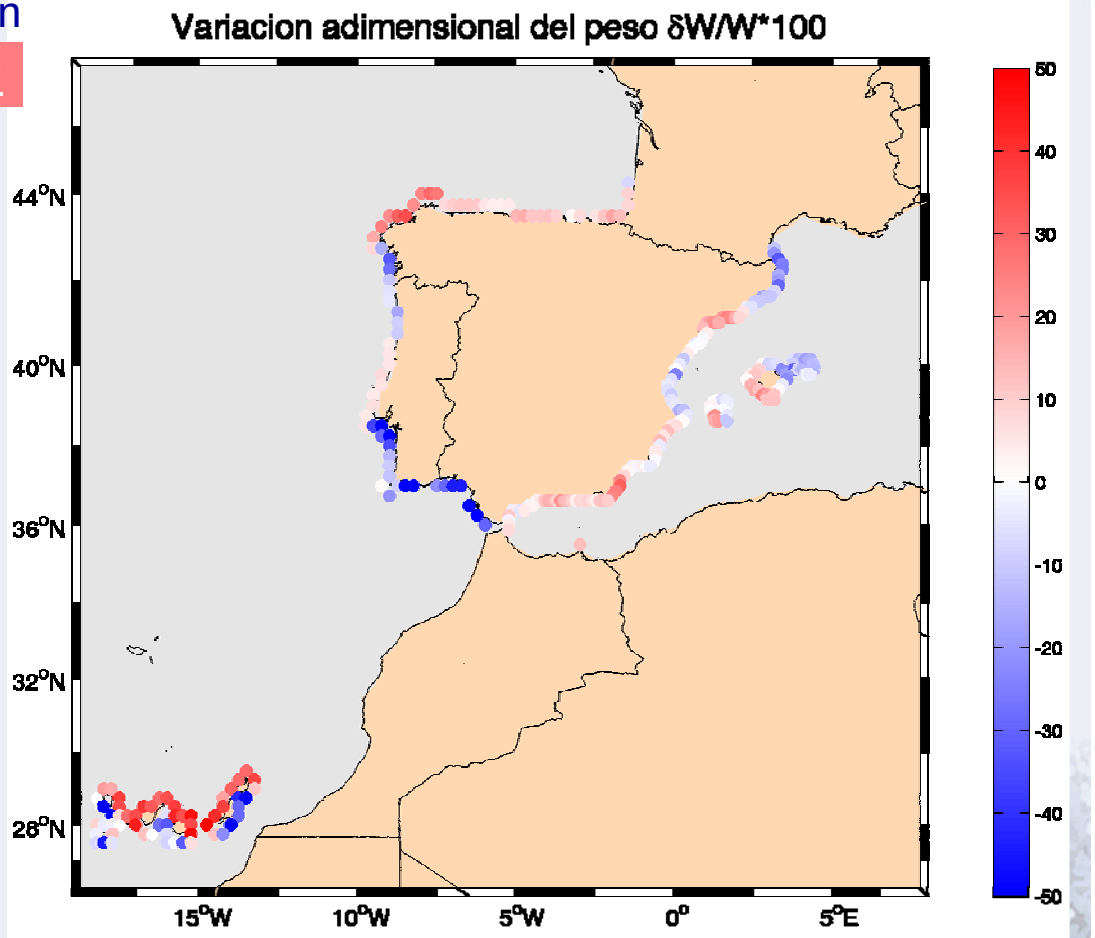
Horizon year: 2050

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Rubble-mound block sizes variation

Non depth-limited wave!

DATOS REPRESENTATIVOS		
Costa Norte Gallega y Norte Canarias	**Costa Mediterránea**	**Golfo de Cádiz**
↑ 40 %	**-10/10 %**	**↓ 40 %**



Horizon year: 2050

WAVE CLIMATE VARIABILITY
Effects on the spanish coast

- En estudios anteriores, el único indicador de cambio climático era el retroceso de la costa por efecto de la sobreelevación del nivel medio del mar.

- Se pone de manifiesto la importancia del oleaje y especialmente la variabilidad que la frecuencia e intensidades de los temporales pueden tener sobre la costa.

- Los reanálisis de oleaje y de nivel del mar (previa calibración) permiten realizar el análisis de tendencias y de variabilidad climática (44 años de datos)

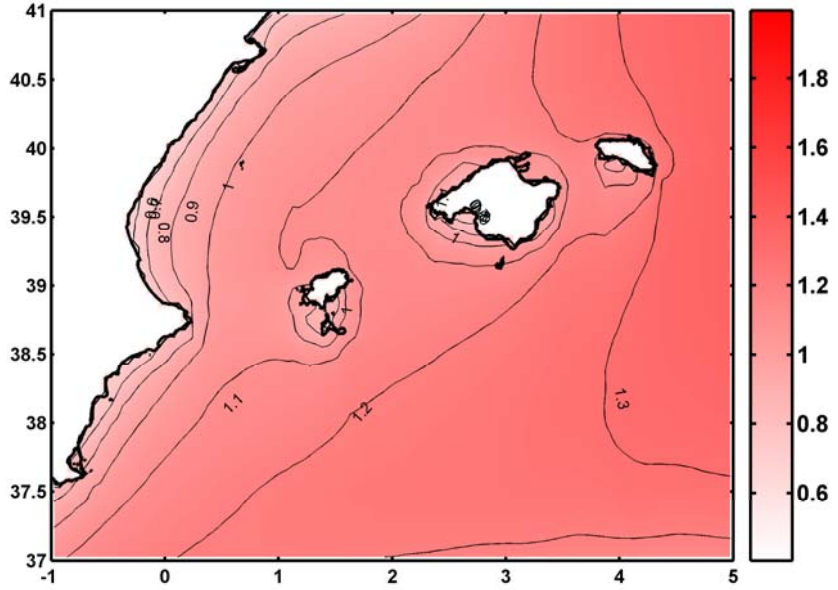
- Las metodologías de análisis de tendencias desarrolladas son rigurosas

CALIBRATION

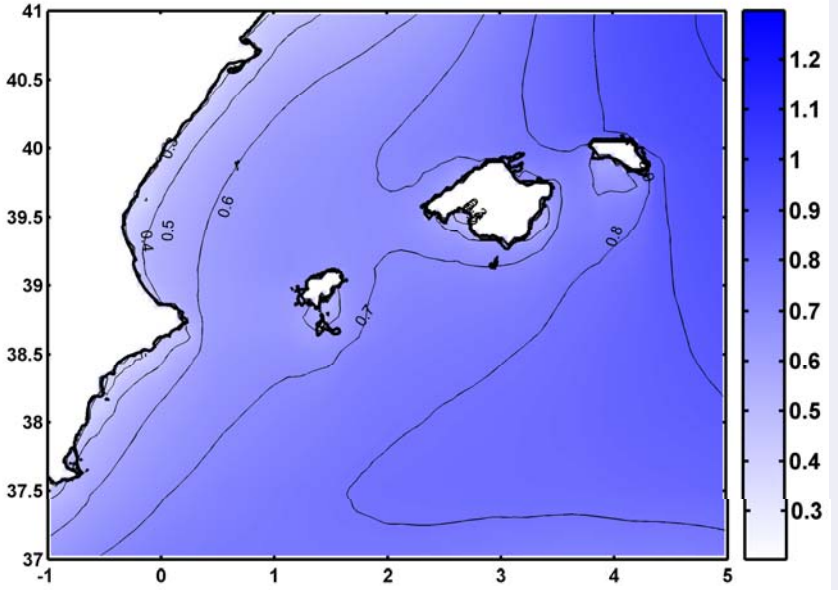
Reanalysis data. Spatial

Spatial variation of calibrated annual distribution of SWH

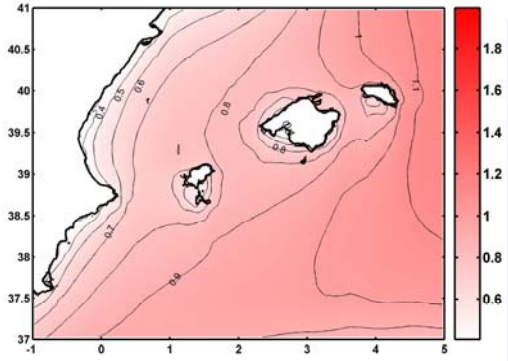
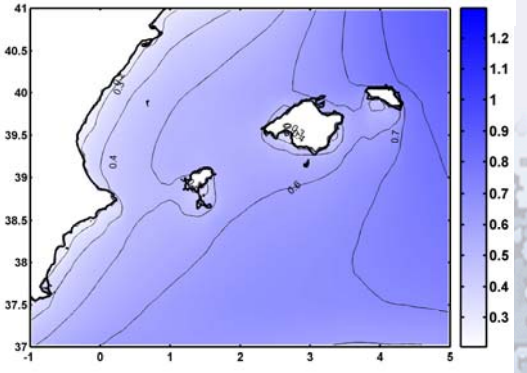
$\mu(\mathbf{x})_{ANUAL}$



$\sigma(\mathbf{x})_{ANUAL}$



Before calibration



Before calibration