Future wave climate in the Mediterranean Sea from a large ensemble of 31 GCM-RCM wave simulations

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Olympic Harbour, Barcelona (Gloria Storm, January 2020)

COASTAL ENGINEERING - ATMOSPHERE PHYSICS - CLIMATE CHANGE
MeteOcean

imedea CSIC Universitat de les Illes Balears
EXCELENCIA MARÍA DE MAEZTU 2023-2027

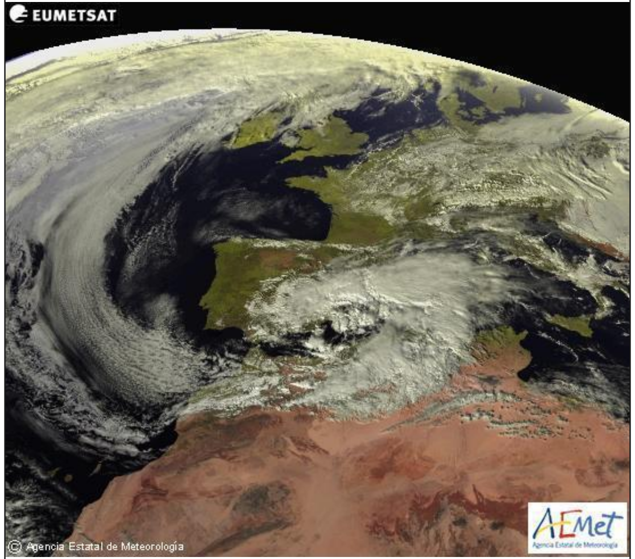
The Mediterranean Sea, a fetch limited environment

Figure adapted from *Soukissian et al., 2018*

Waves in the Mediterranean: **Hs > 8 m and H > 12 m** (example: Gloria Storm, 2020)

Gloria Storm

January 19-24, 2020

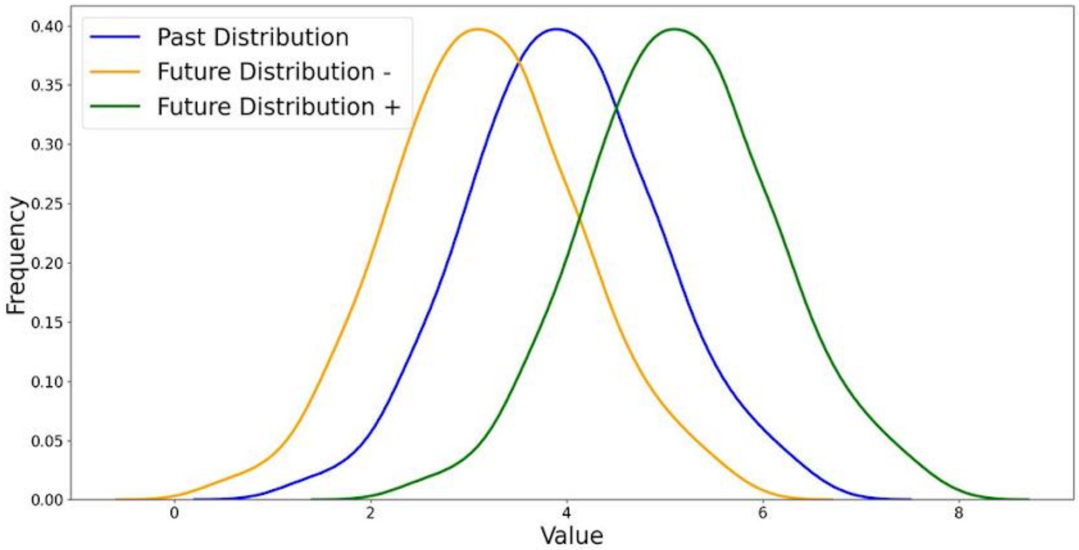


Satellite image of the storm Gloria.

Source: EUMETSAT

Gloria storm hits the eastern coasts of Spain

Sources: Majorca daily bulletin, elDiario.es, pexels.com



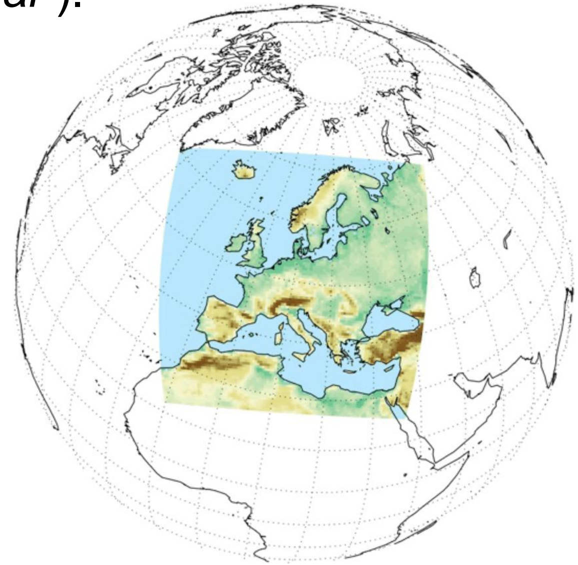
To investigate the future changes in the Mediterranean wave climate from climate projections under RCP8.5 scenario (*Jacob et al. 2014; 2020*).

I. Data and numerical modelling

II. Future mean and intense wave climate: seasonal analysis

III. Changes in future extreme waves: Extreme Value Theory

EURO-CORDEX:
Ensemble of Regional Climate Models (RCMs) downscaled from General Circulation Models (GCM) for historical and future period under **RCP8.5 scenario** (“*business as usual*”).



EURO-CORDEX model domain at 0.11º resolution
Jacob etal., 2020

- **Ensemble of 31 GCM-RCMs over the Mediterranean:**

1. From the work of *Lira Loarca et al., 2023:*
   - **21** GCM-RCMs models
   - Wave model: **WavewatchIII** (WW3)

2. From the present work:
   - **10** GCM-RCMs models
   - Wave model: **SCHISM**

- **Reference wave hindcast from *Lira-Loarca et al., 2022***

Generation of wave historical and future simulations:

Atmospheric fields from GCM-RCMs *(u10,v10)*

↓ *

SCHISM / WW3
Wave spectral model

↓

Hourly outputs of wave parameters
(Hs, ~~Tp, Dp~~)

* 3 periods considered:
- Historical: **1979 - 2005**
- ~~Mid-century: **2034 - 2060**~~
- End-century: **2074 - 2100**

Methodology

Methodology

For each season, we compute the Hs **difference** between the **historical** and **end-century periods** for the **mean** and **0.95 quantile** statistical indicators:

$$\Delta_{H_s}^{mean} = \frac{1}{N}\sum_{i}^{N}\{Hs_{end}^{mean}(i) - Hs_{hist}^{mean}(i)\}$$

$$\Delta_{H_s}^{Q^{0.95}} = \frac{1}{N}\sum_{i}^{N}\{Hs_{end}^{Q^{0.95}}(i) - Hs_{hist}^{Q^{0.95}}(i)\}$$

N = 31

Methodology

GCM	RCM	Model	Realization	Weight
CCCma-CanESM2	CCLM4-8-17	WW3	r1i1p1	1
MIROC-MIROC5	CCLM4-8-17	WW3	r1i1p1	1
MPI-M-MPI-ESM-LR	RCA4	WW3	r1i1p1	1/4
MPI-M-MPI-ESM-LR	HIRHAM5	WW3	r1i1p1	1/4
MPI-M-MPI-ESM-LR	COSMO-crCLIM-v1-1	SCHISM	r1i1p1	1/4
MPI-M-MPI-ESM-LR	RegCM4-6	SCHISM	r1i1p1	1/4
NCC-NorESM1-M	RCA4	WW3	r1i1p1	1/5
NCC-NorESM1-M	HIRHAM5	WW3	r1i1p1	1/5
NCC-NorESM1-M	COSMO-crCLIM-v1-1	WW3	r1i1p1	1/5
NCC-NorESM1-M	REMO2015	SCHISM	r1i1p1	1/5

$$\Delta_{H_s}^{mean} = \frac{1}{\sum_i^N w_i} \sum_i^N w_i \left[Hs_{end}^{mean}(i) - Hs_{hist}^{mean}(i) \right]$$

$$\Delta_{H_s}^{Q^{0.95}} = \frac{1}{\sum_i^N w_i} \sum_i^N w_i \left[Hs_{end}^{Q^{0.95}}(i) - Hs_{hist}^{Q^{0.95}}(i) \right]$$

Methodology

IPCC guidelines on robustness of multi-model mean results:

1. **Sign of change:** how many models show > 0 or < 0 change
2. **Variability threshold:** $\gamma = \sqrt{2/20} * 1.645 * \delta_{1yr}$

where δ_{1yr} is the interannual standard deviation measured in a linearly detrended modern period.

•**Robust Signal (No Overlay):**

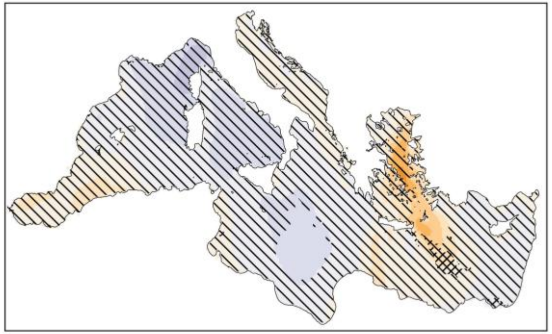
- ≥66% of models show a change in Hs greater than the variability threshold.
- ≥80% of all models agree on the sign of the change.

•**No Change or No Robust Signal (Diagonal Lines):**

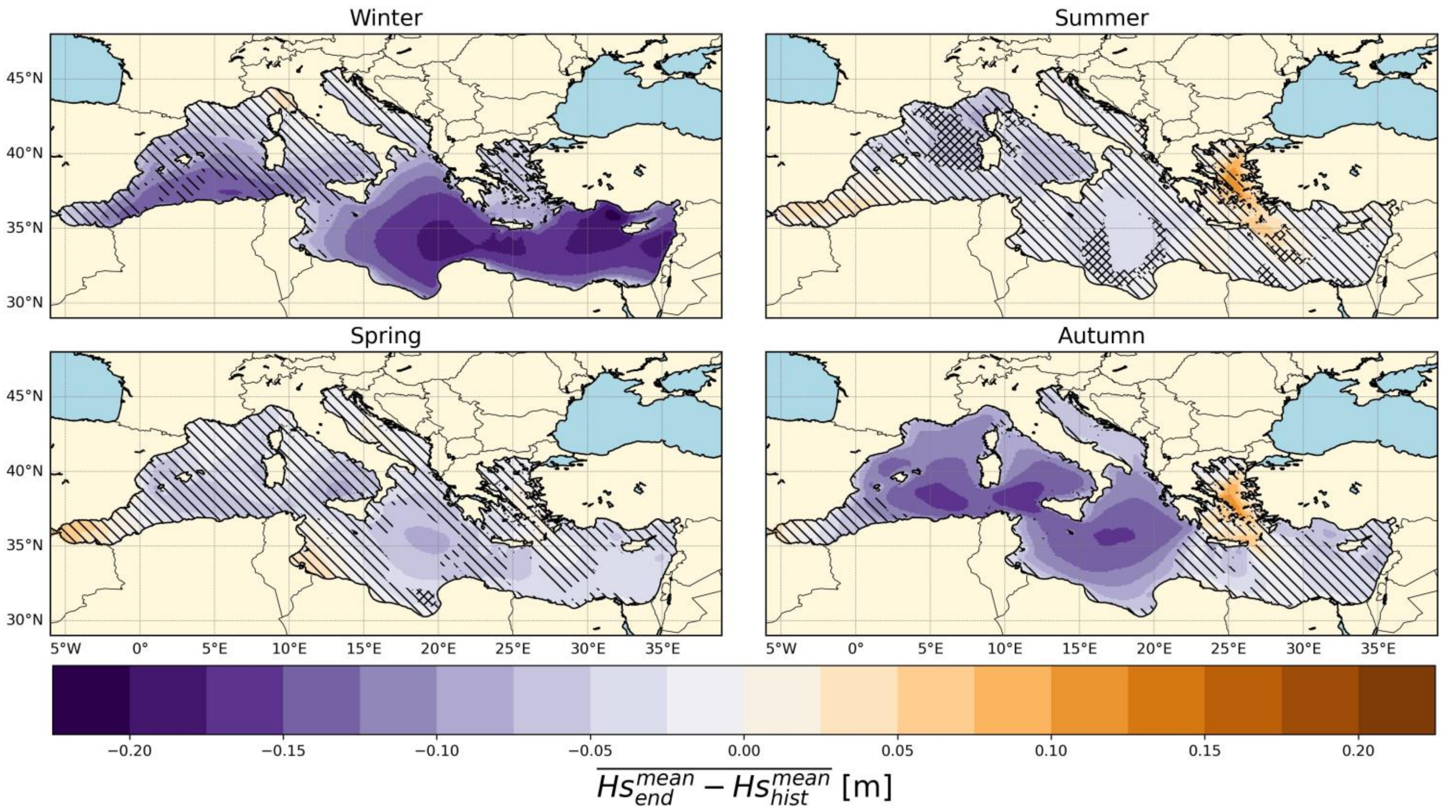
- <66% of models show a change in Hs greater than the variability threshold.

•**Conflicting Signal (Crossed Lines):**

- ≥66% of models show a change in Hs greater than the variability threshold.
- <80% of all models agree on the sign of the change.

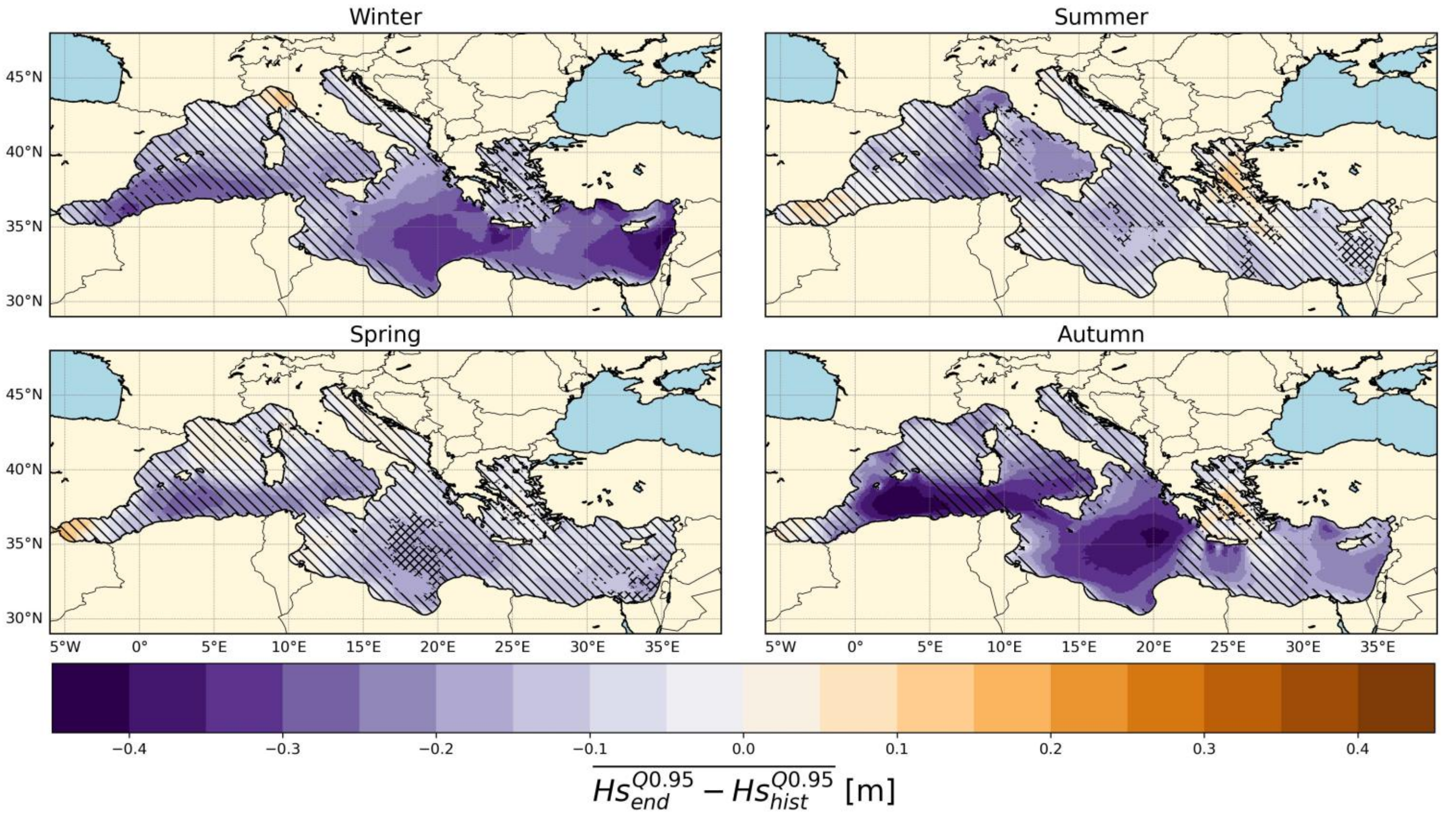


Results: Mean wave climate



Hatched areas: IPCC guidelines on robustness of multi-model mean results (*IPCC, 2023*)

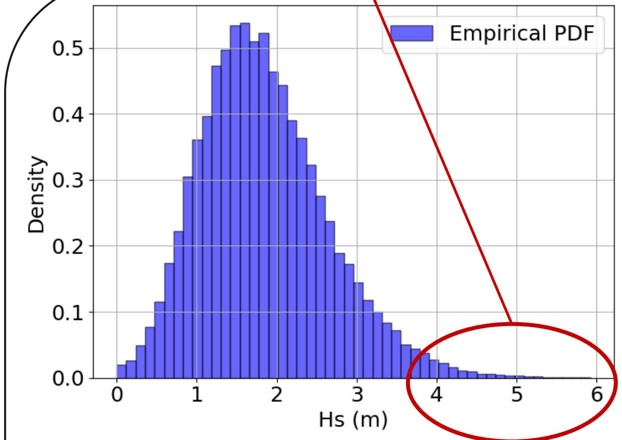
Results: Intense wave climate

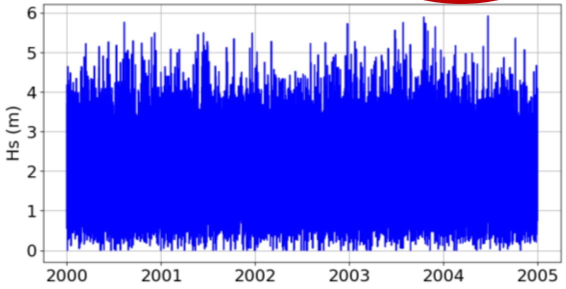


Hatched areas: IPCC guidelines on robustness of multi-model mean results (*IPCC, 2023*)

Extreme Value Theory

"To characterize the unusual rather than the usual" *Coles, 2001*





Hs time series of one single point

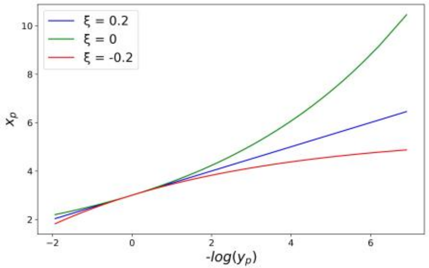
Probability distributions for extremes

Generalized Extreme Value (GEV)

$$F(x;\mu,\sigma,\xi)=\begin{cases}\exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} & \text{if } \xi\neq 0\\ \exp\left\{-\exp\left(-\frac{x-\mu}{\sigma}\right)\right\} & \text{if } \xi=0\end{cases}$$

"Block maxima approach"

Return level computation



Methodology

$$\Delta_{H_s}^{RL100y} = \frac{1}{\sum_i^N w_i} \sum_i^N w_i \left[Hs_{end}^{RL100y}(i) - Hs_{hist}^{RL100y}(i) \right]$$

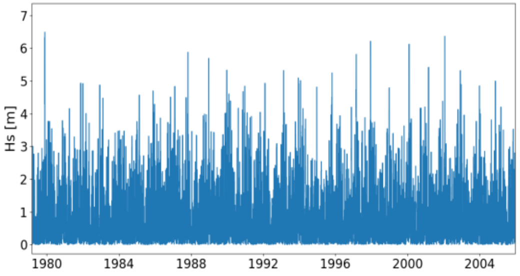
Reminder: the studied periods are **1979-2005** and **2074-2100**

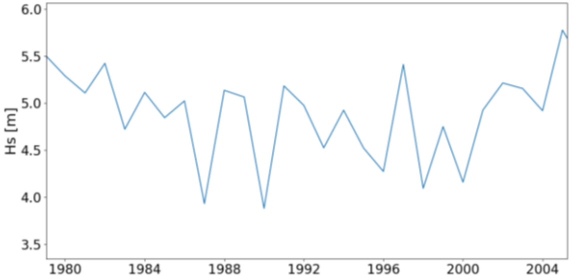
→ Low number of extreme events (**27 years** per model)

→ Potential **large uncertainties** associated with the computation of return levels

Methodology

For every model Mx, x ϵ [1,…,N]



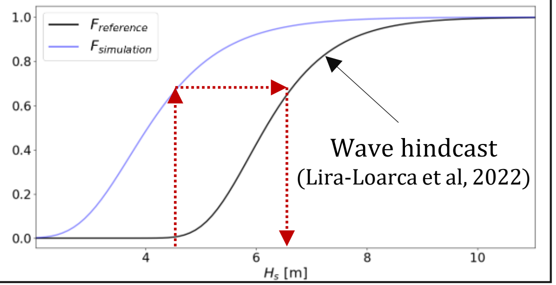


Bias correction

$$X^* = F_{hind}^{-1}[F_{hist}(X)]$$

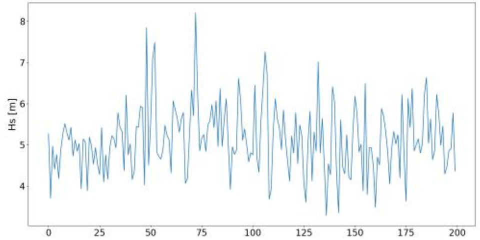
F is the Cumulative Distribution function of the GEV distribution:

$$F(x;\mu,\sigma,\xi) = \begin{cases} \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} & \text{if } \xi \neq 0 \\ \exp\left\{-\exp\left(-\frac{x-\mu}{\sigma}\right)\right\} & \text{if } \xi = 0 \end{cases},$$

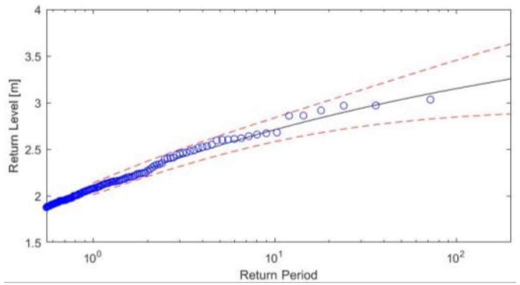


X_1^* … X_i^* … X_N^*

One unique distribution of **27*N** bias-corrected annual maxima

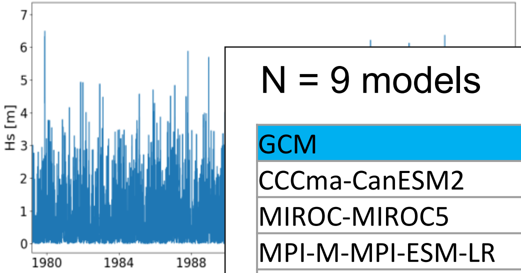


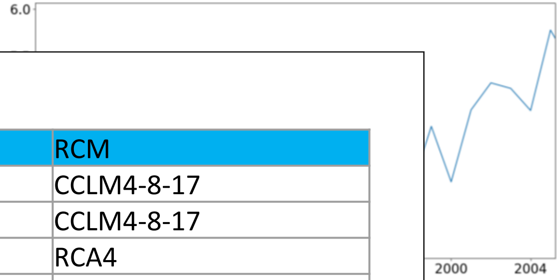
GEV distribution fit and return levels



Methodology

For every model Mx, x ϵ [1,…,N]





N = 9 models

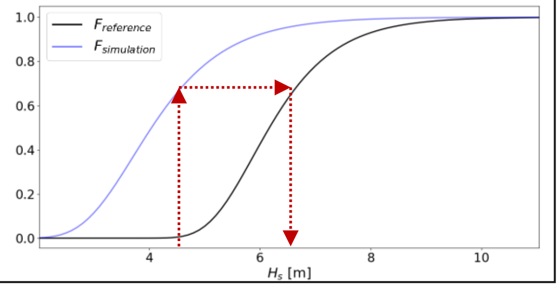
GCM	RCM
CCCma-CanESM2	CCLM4-8-17
MIROC-MIROC5	CCLM4-8-17
MPI-M-MPI-ESM-LR	RCA4
NCC-NorESM1-M	HIRHAM5
CNRM-CERFACS-CNRM-CM5	COSMO-crCLIM-v1-1
IPSL-IPSL-CM5A-MR	REMO2015
MOHC-HadGEM2-ES	ALADIN63
ICHEC-EC-EARTH	RCA4
ICHEC-EC-EARTH	RACMO22E (r3i1p1)

Bias correction

$$X^* = F_{hind}^{-1}[F_{hist}(X)]$$

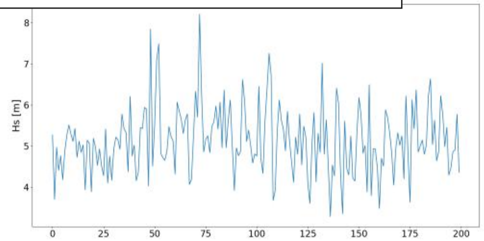
F is the Cumulative Distribution function of the GEV distribution:

$$F(x;\mu,\sigma,\xi) = \begin{cases} \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} & \text{if } \xi \neq 0 \\ \exp\left\{-\exp\left(-\frac{x-\mu}{\sigma}\right)\right\} & \text{if } \xi = 0 \end{cases},$$

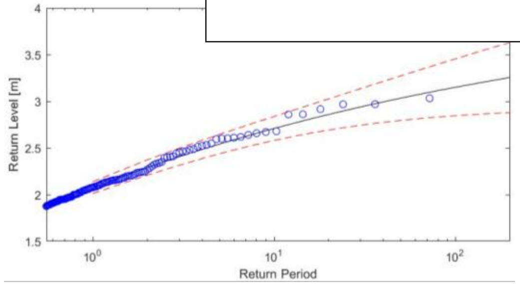


X_1^* . . X_i^* . . X_N^*

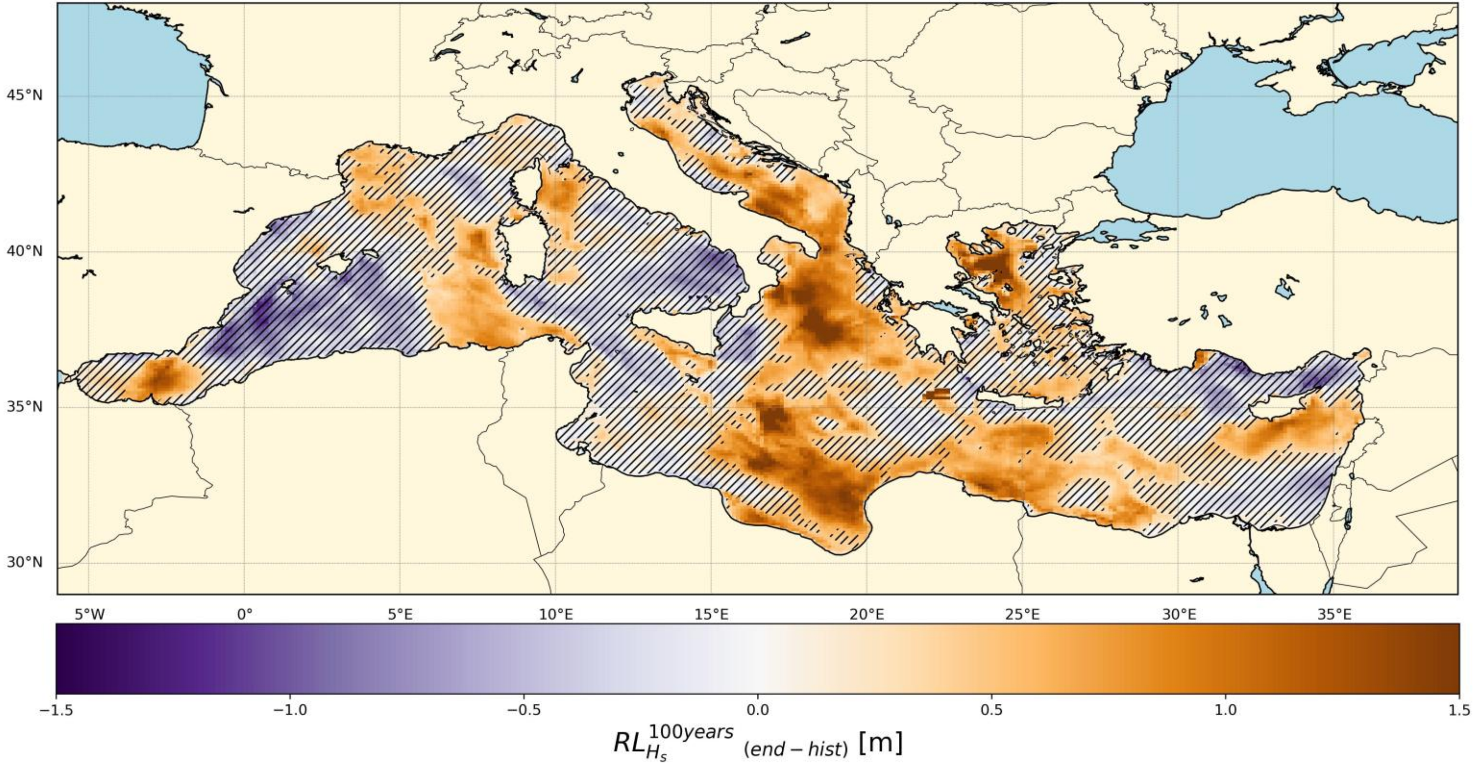
N bias-



GEV distributi



Results



Hatched areas where: $\left|\Delta^{RL100y}_{H_{s(end-hist)}}\right| < CI\Delta_{95\%}(RL^{100y}_{Hs\_hist})$

Conclusions

- In agreement with previous studies, outcomes suggest **statistically significant reductions** in both the **mean** and intense wave climate (**quantile 0.95**) for the significant wave height (**H_s**) and the peak period (**T_p**) variables.

- Substantial **multi-model agreement on the change of wave direction** (peak direction – **D_p**) in several regions.

- Analysis of return levels shows that **Hs 100-year return levels** are projected to **increase by up to 1.5 m** in some regions.

- Additional uncertainty analyses indicate limited areas where significant changes are observed.

Earth's Future

RESEARCH ARTICLE

10.1029/2024EF004992

Key Points:

- Robust results from the large ensemble of GCM-RCM indicate an overall average reduction of the mean and intense Mediterranean wave climate
- Future shifts in extreme events differ from the rest of the distribution, as robust increases in H_s 100-year return levels are projected

Future Wave Climate in the Mediterranean Sea and Associated Uncertainty From an Ensemble of 31 GCM-RCM Wave Simulations

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[1]Mediterranean Institute for Advanced Studies (UIB-CSIC), Esporles, Spain, [2]Department of Civil, Chemical and Environmental Engineering, University of Genoa, Genoa, Italy, [3]Department of Physics, University of the Balearic Islands, Palma, Spain

Thank you

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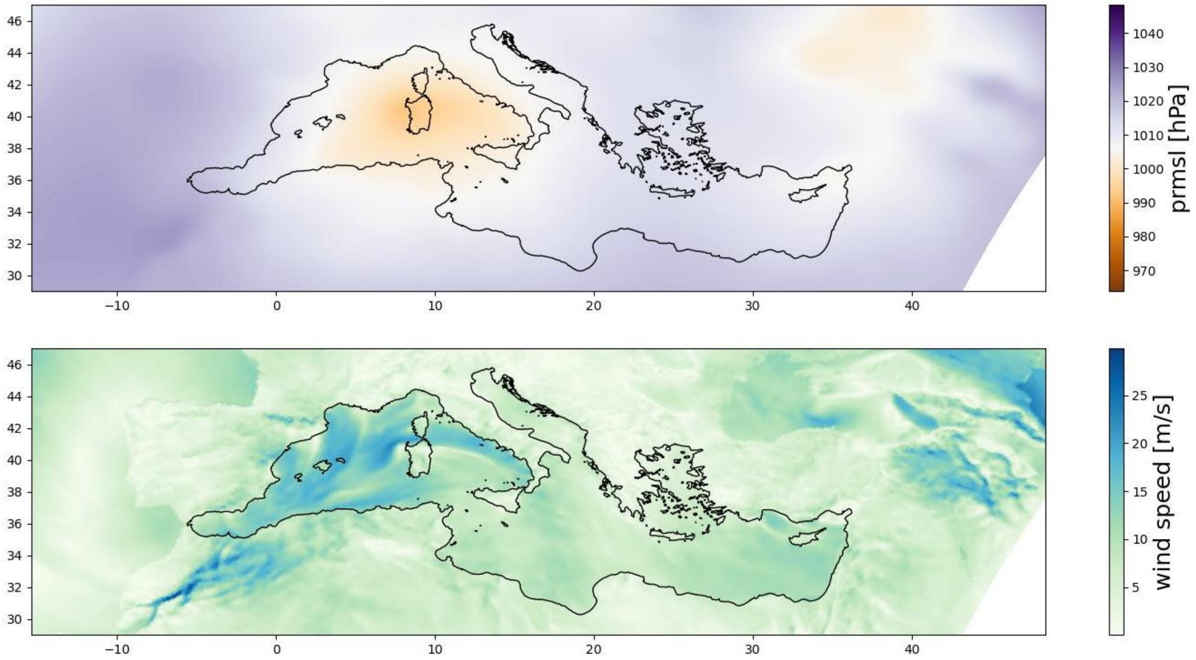
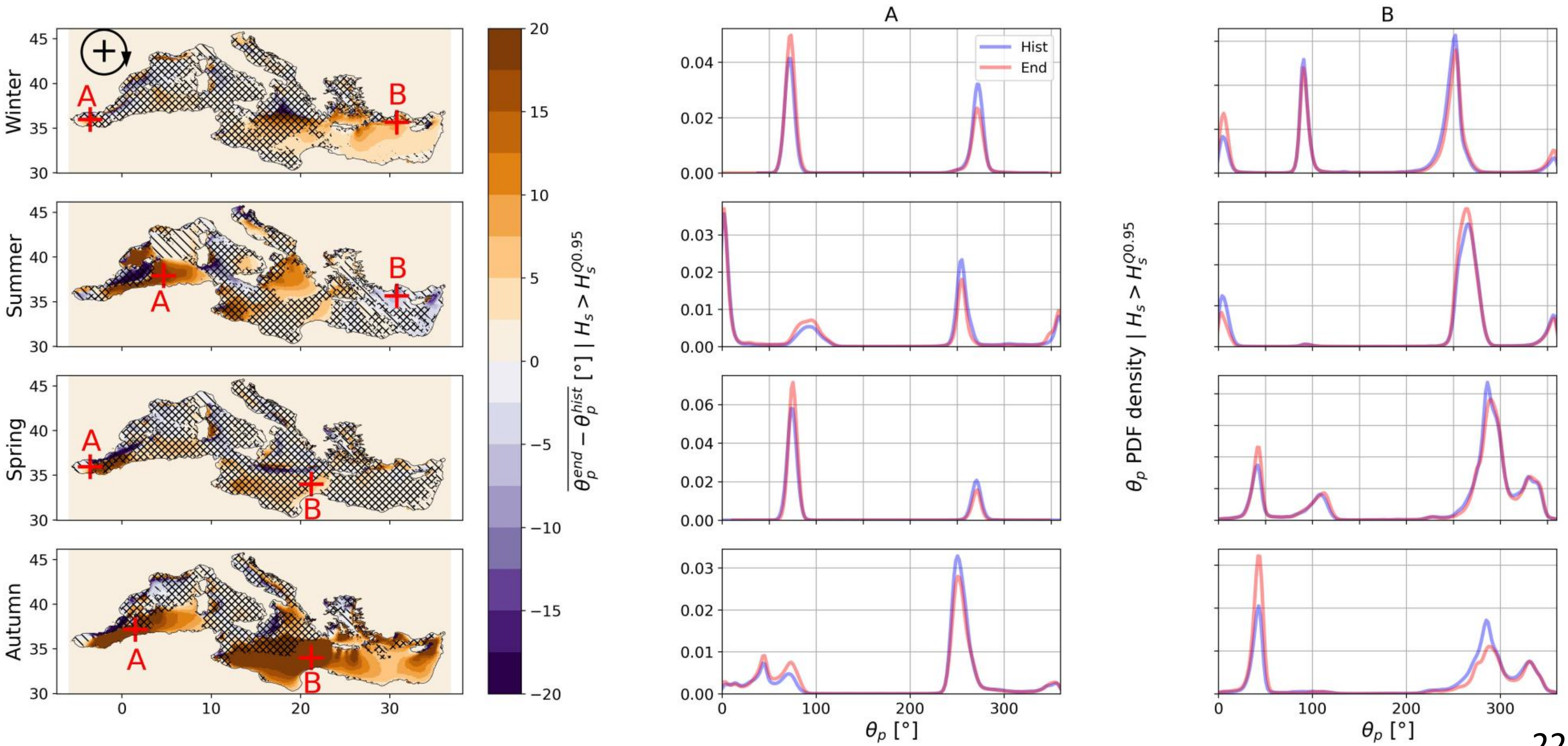
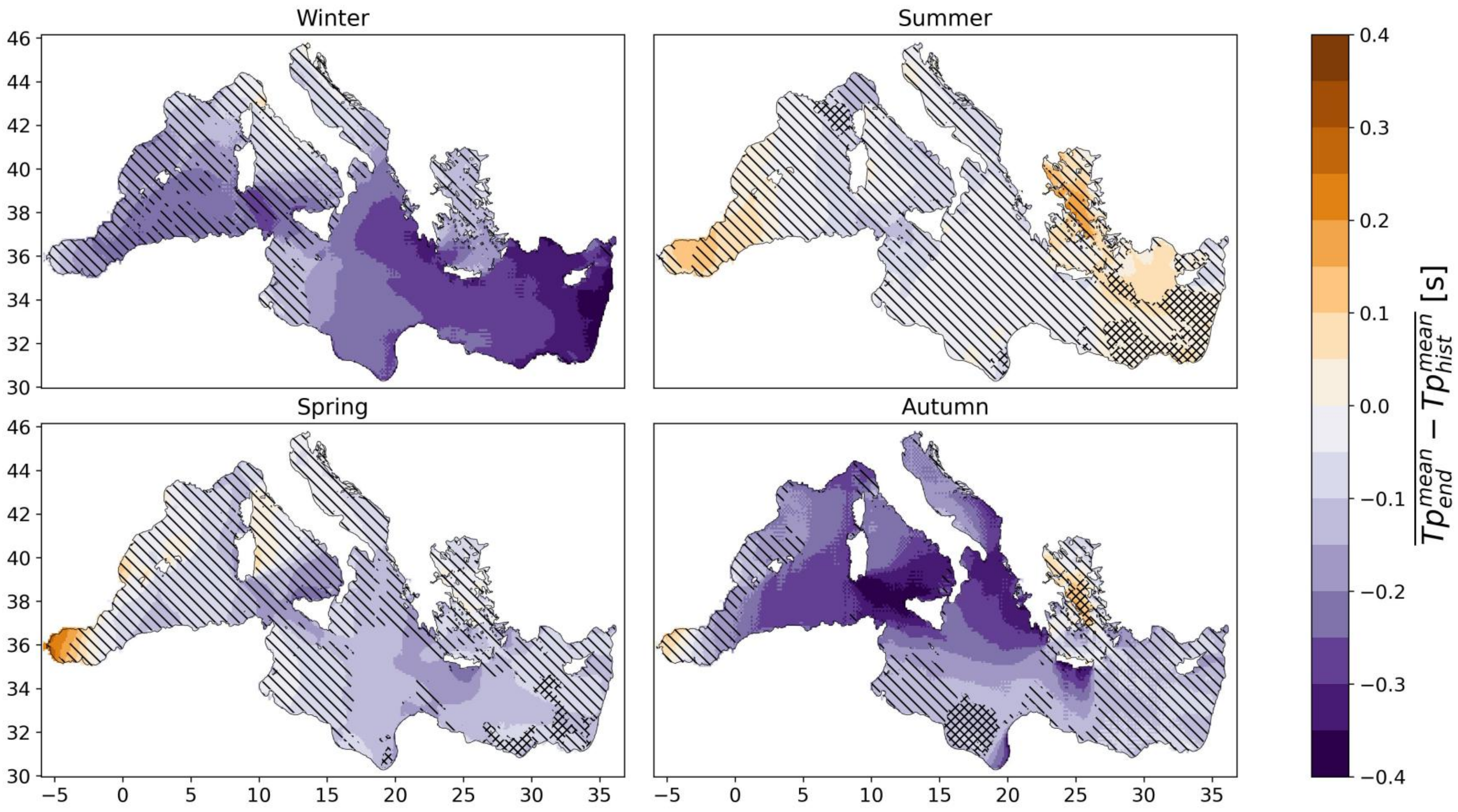
Atmospheric forcings

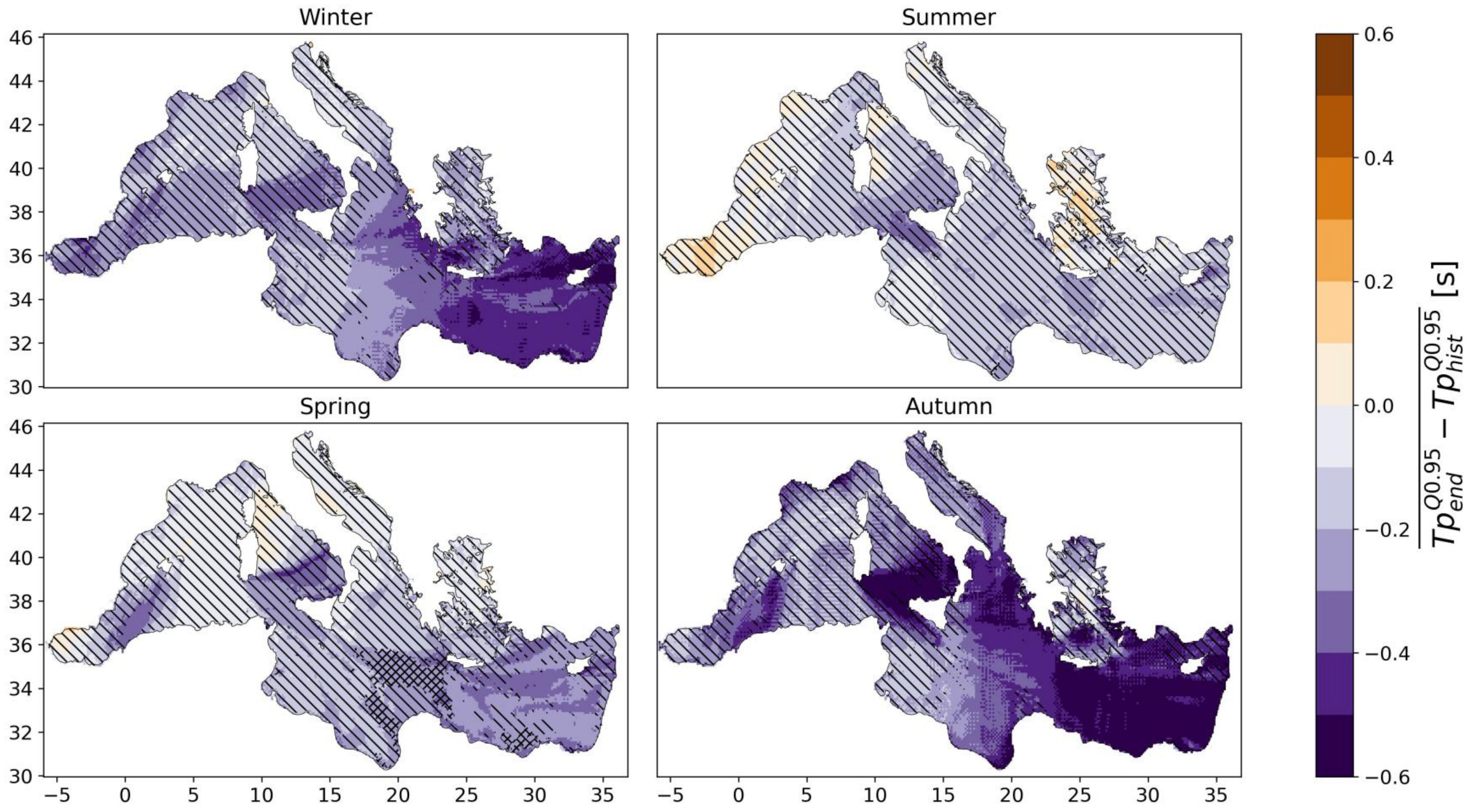


Example of a snapshot of pressure and wind fields from one GCM-RCM

Results: Intense wave climate




Winter
Summer
Spring
Autumn
46
44
42
40
38
36
34
32
30
−5
0
5
10
15
20
25
30
35
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
$\overline{Tp_{end}^{mean}} - \overline{Tp_{hist}^{mean}}$ [s]


Winter
Summer
Spring
Autumn
46
44
42
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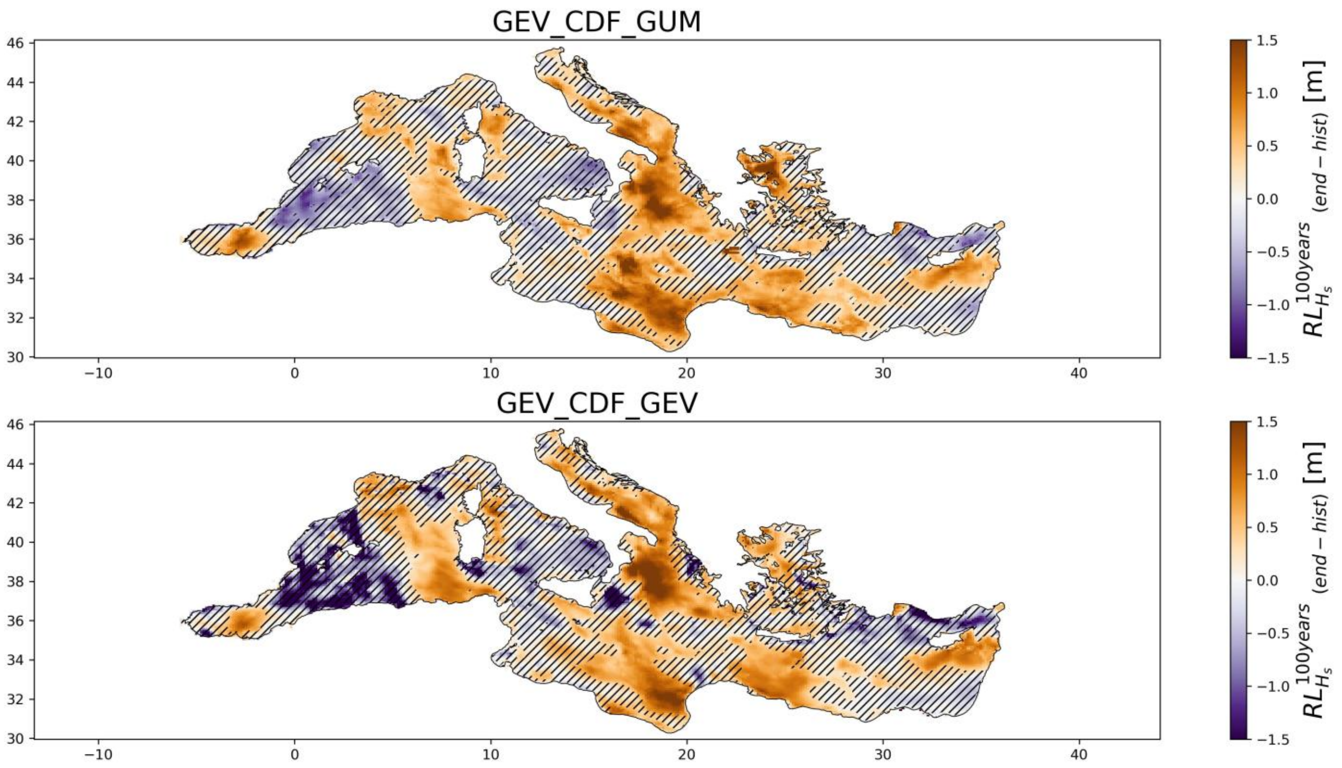
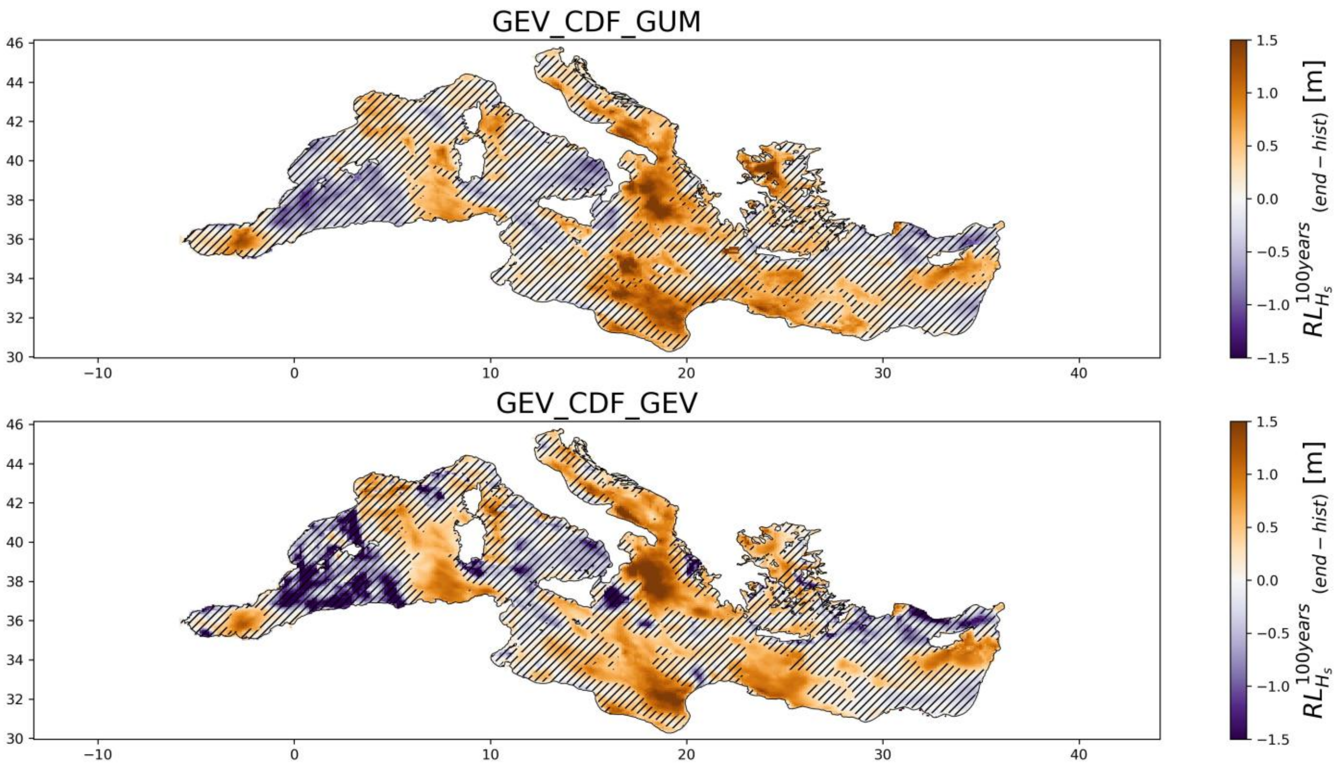
5
10
15
20
25
30
35
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
$\overline{Tp_{end}^{Q0.95} - Tp_{hist}^{Q0.95}}$ [s]

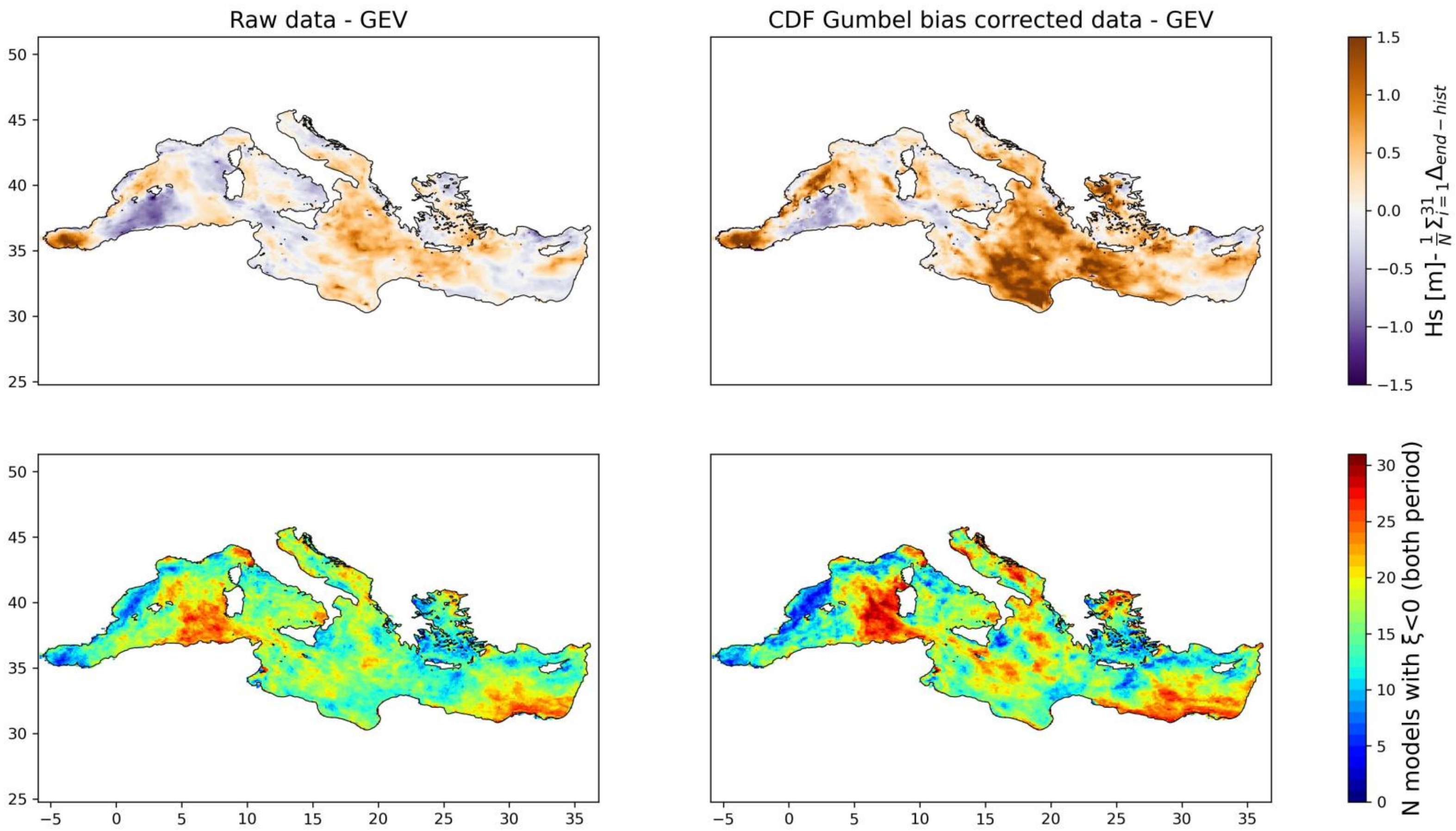


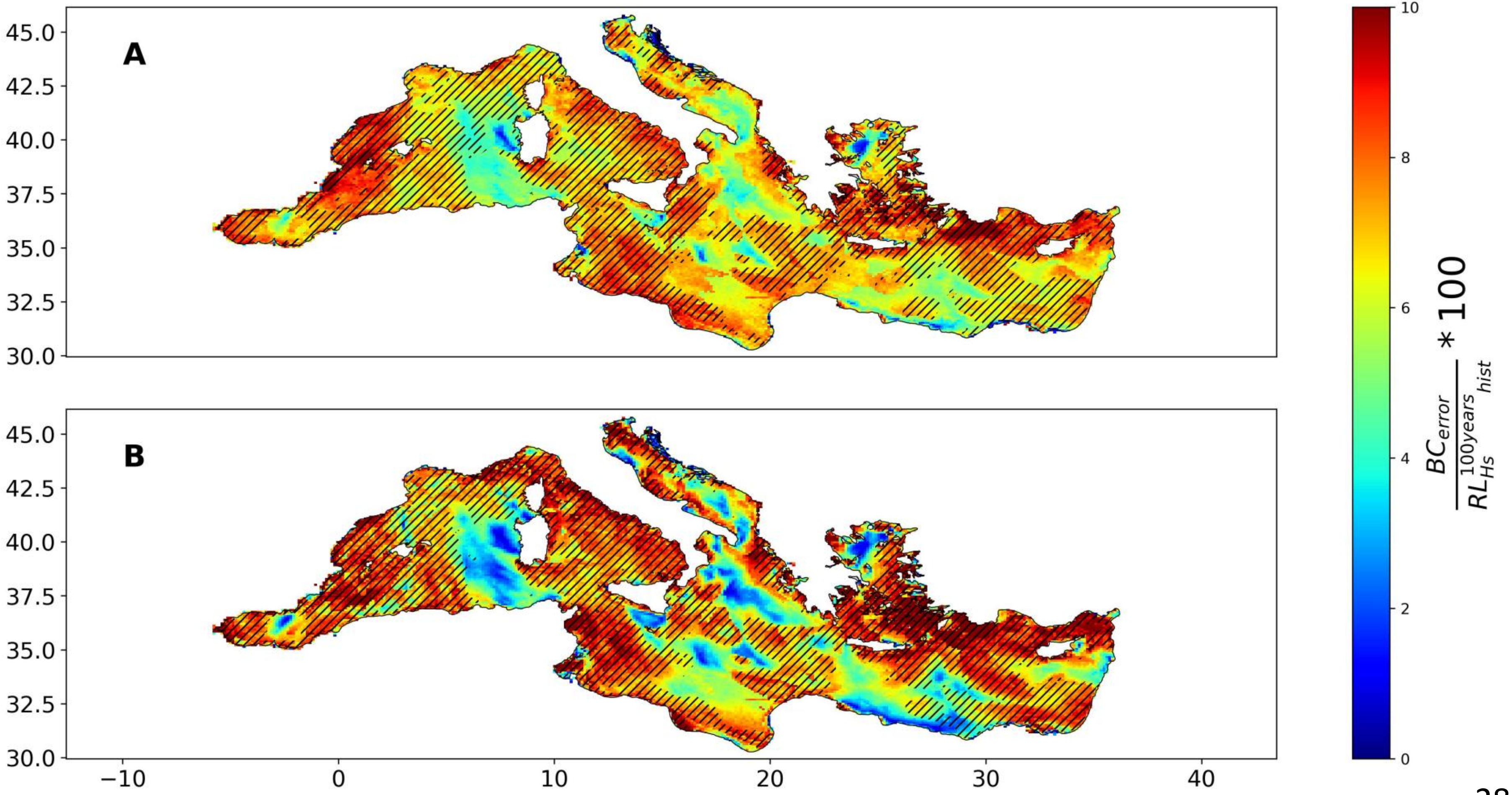
Hatched areas where: $\Delta^{RL100y}_{H_{s(end-hist)}} < (RL^{RL80\%100y}_{Hs\_hist} - RL^{RL20\%100y}_{Hs\_hist})$



Hatched areas where: $\Delta^{RL100y}_{H_{s(end-hist)}} < (RL^{RL95\%100y}_{Hs\_hist} - RL^{RL5\%100y}_{Hs\_hist})$

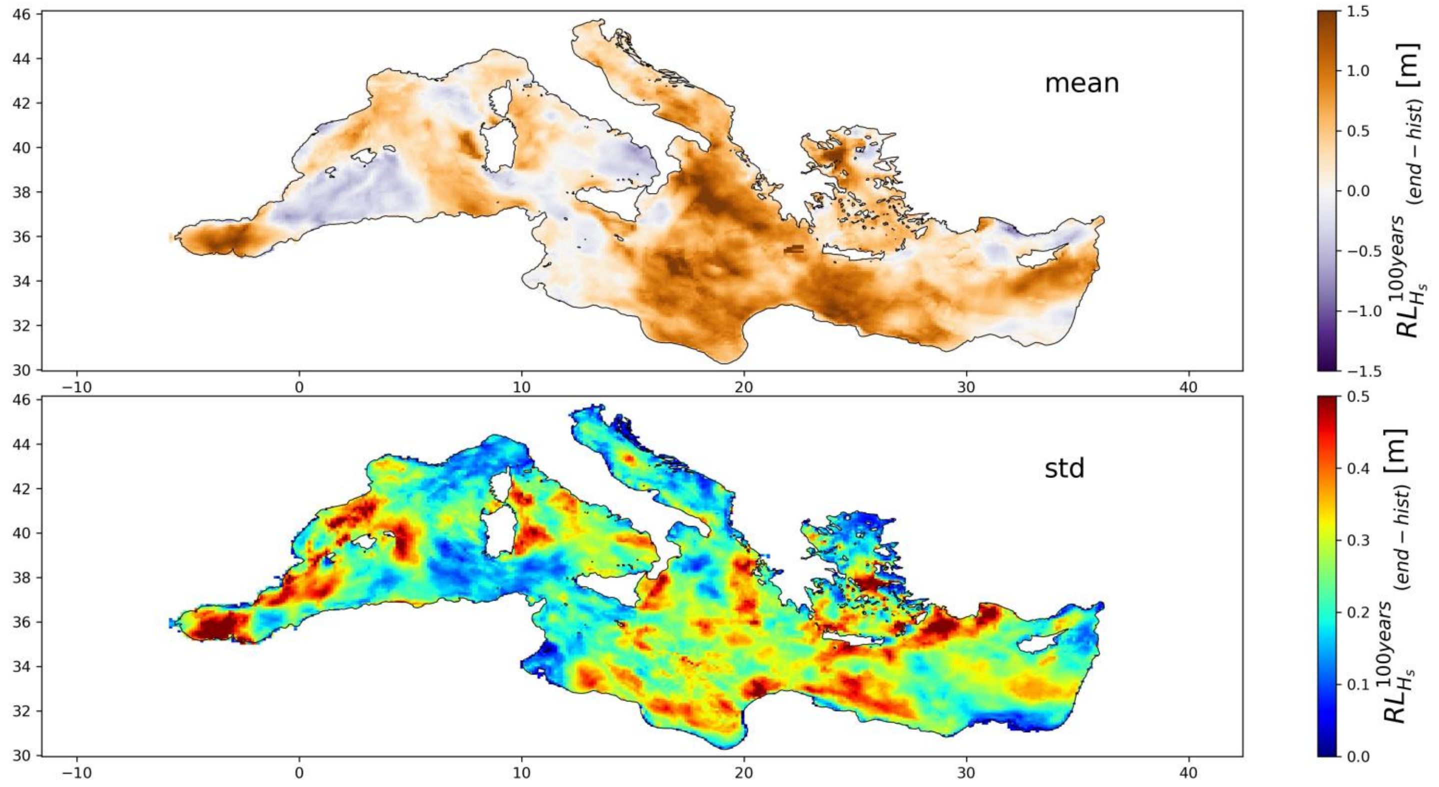
31 models | End [2074-2100] - Hist [1979-2005] | RP = 100 years




A
B
45.0
42.5
40.0
37.5
35.0
32.5
30.0
−10
0
10
20
30
40
10
8
6
4
2
0
$\frac{BC_{error}}{RL_{Hs}^{100years}{}_{hist}} * 100$

Random selection of 9 GCM-RCM

10 combinations of 9 models - Bias correction method: GUMBEL distribution



Random selection of 9 GCM-RCM