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

Wave climate projection in the Western European seas under SSP5-8.5 climate change scenario

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Post-doctoral study at Saint-Venant Hydraulics Laboratory (LHSV) from July 2024 to August 2025

25/09/2025

Context and objectives

<u>Context:</u>

- **Climate Change** causes significant changes in several metocean variables (*e.g. :* temperature, mean sea level)

- **How will the wave conditions evolve in Western European Seas?**
    - No clear trends identified yet
    - Ongoing research on this topic

- Need to anticipate possible evolution of marine hazards in order to prepare adaptation plans

- **EDF / LHSV lab expertise in wave modelling**
    - ⇒ *TELEMAC-MASCARET* software (*TOMAWAC* for sea states , *TELEMAC-2D* for storm surges)
    - ⇒ Regional reanalysis database *ANEMOC3* 1979-2024 (46 years)

<u>Objectives of the current study:</u>

- ❑ **Generate** GCM-based datasets using *ANEMOC3* regional model
- ❑ **Validate historical-period** data against *ANEMOC3*
- ❑ Analyze **wave climate evolution**
- ❑ **Compare** with a state-of-the-art database (*Meucci 2024*)
  Meucci, A., Young, I. R., Trenham, C., & Hemer, M. (2024). An 8-model ensemble of CMIP6-derived ocean surface wave climate. *Scientific Data*, *11*(1), 100

Focus on Western European Seas (North-Eastern Atlantic area)

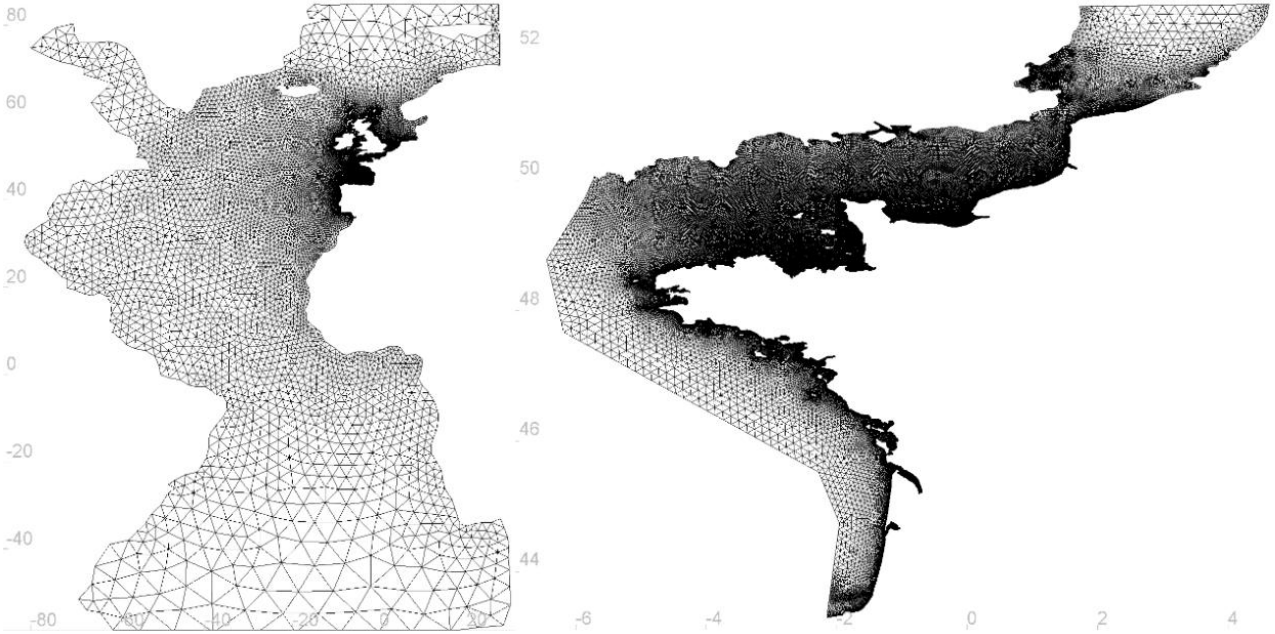

Figure 2. ANEMOC-3 oceanic (left panel) and coastal (right panel) domains.

Teles M., Weiss M., Benoit M. (2022) Assessment of the ANEMOC-3 sea state hindcast database for modelling a series of energetic winter storms along the French coast, XVIIèmes Journées Nationales Génie Côtier – Génie Civil, Chatou, France, pp 171-182.

Summary

1. Western European Seas wave databases

   Meucci et al. (2024) + *ANEMOC3* reanalysis + *TOMAWAC/GCM* simulations

2. Performance of the CMIP6 GCM-based datasets for the historical period

3. Evolution of wave climate under SSP5-8.5 climate change scenarios

4. Conclusion and Perspectives

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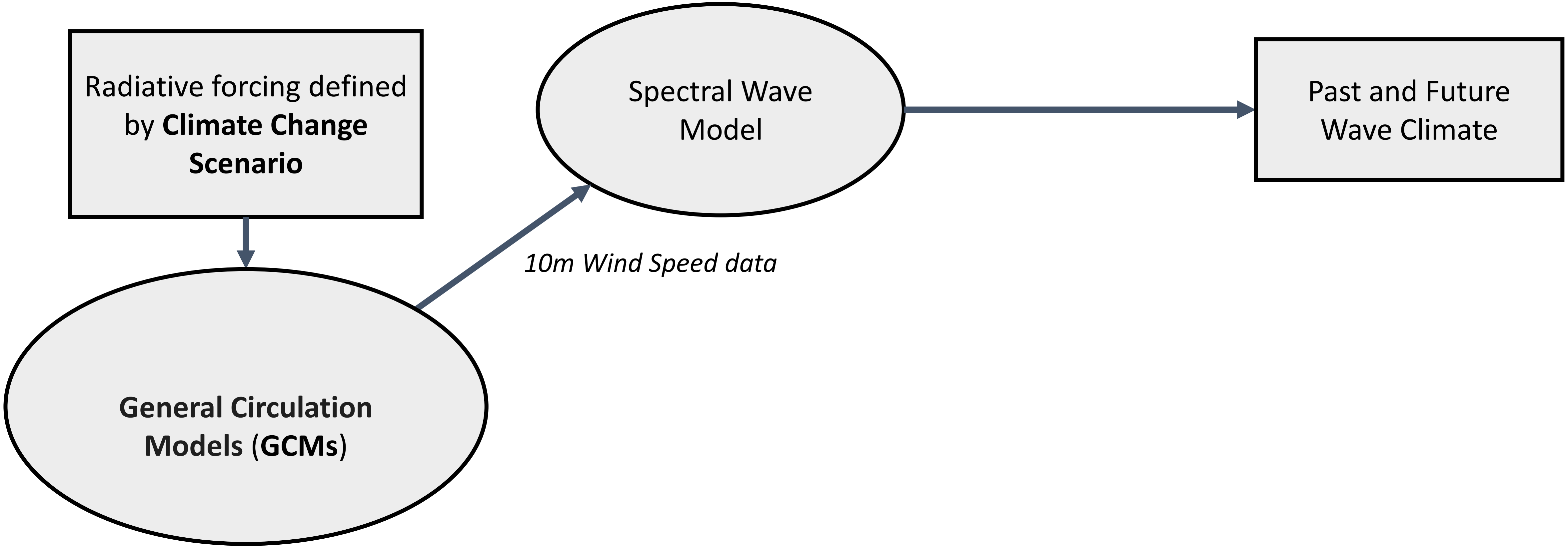
State-of-the-art methodology for the generation of wave climate dynamical projections



Meucci et al. (2024) data

Radiative forcing defined by **Climate Change Scenario**
SSP5-8.5 and SSP1-2.6

8 CMIP6 GCMs
Global Domain

ACCESS-CM2
AWI-CM-1-1-MR
CMCC-CM2-SR5
EC-Earth3
IPSL-CM6A-LR
KIOST-ESM
MPI-ESM1-2-LR
MRI-ESM2-0

10m Wind data
(dt=3h)

Spectral Wave Model
WaveWatchIII
Global Domain

Past and Future Wave Climate:

- Global Grid of **0.5°x 0.5°**
- Time-step of **3h**
- **1985-2014** (30 years) for historical period, and **2071-2100** (30 years) for future period
- **Sea State variables**
- Open access

Data from **Meucci, A., Young, I. R., Trenham, C., & Hemer, M. (2024). An 8-model ensemble of CMIP6-derived ocean surface wave climate. *Scientific Data*, *11*(1), 100**.

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H_s => Significant Wave Height

Analysis of H_s for the 8 GCMs and scenario SSP5-8.5

Data from **Meucci, A., Young, I. R., Trenham, C., & Hemer, M. (2024). An 8-model ensemble of CMIP6-derived ocean surface wave climate.** ***Scientific Data*****,** ***11*****(1), 100**.

ANEMOC3 reanalysis (from EDF R&D)

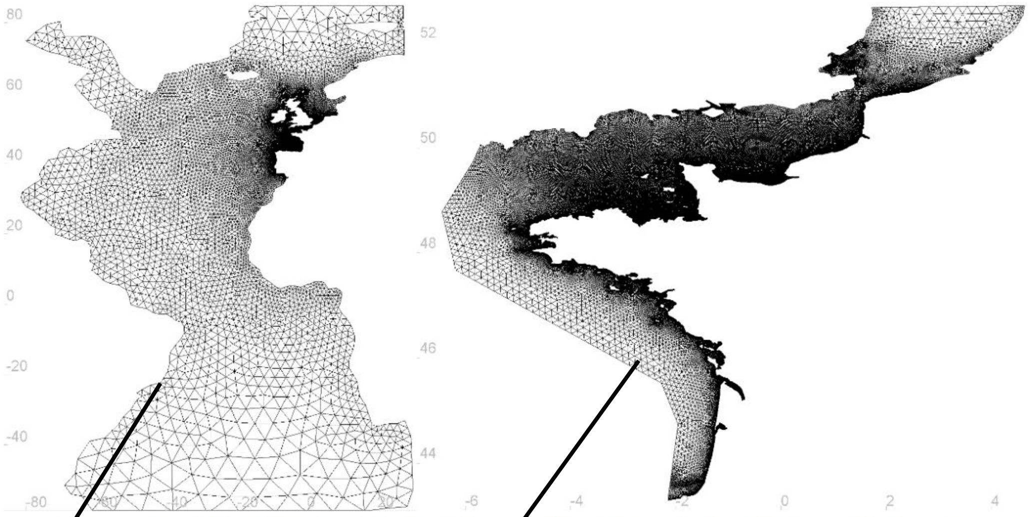
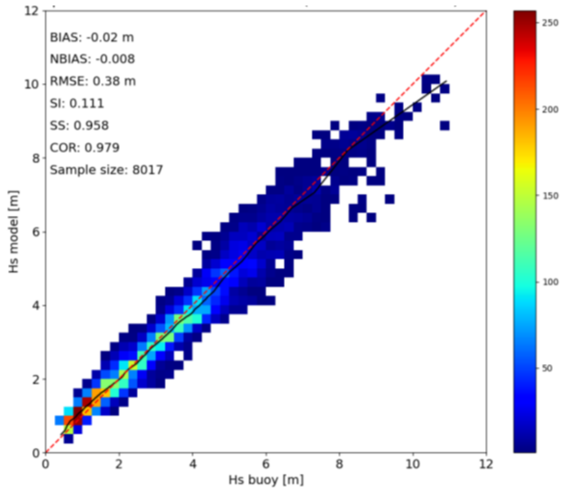


Figure 2. ANEMOC-3 oceanic (left panel) and coastal (right panel) domains.

	ANEMOC-Ocean	ANEMOC-Coastal
Code	*TOMAWAC* (wave model)	*TOMAWAC* (wave model) + *TELEMAC2D* (Hydrodynamic model)
Time Coverage	1979-2024	1979-2024
Wind	CFSR (1979-2010) + CFSv2 (2011-2024)	CFSR (1979-2010) +CFSv2 (2011-2024)
Output dt	1 h	30 min
Spatial discretization	20 km near the coast (12000 nodes)	1 km near the coast (56000 nodes)
Coupling with hydrodynamic model	No	Yes (includes tide and storm surge data)

Teles M., Weiss M., Benoit M. (2022) Assessment of the ANEMOC-3 sea state hindcast database for modelling a series of energetic winter storms along the French coast, XVIIèmes Journées Nationales Génie Côtier – Génie Civil, Chatou, France, pp 171-182.

Calibrated/validated against buoy and satellite data



ANEMOC3-Coastal comparison with Belle-île buoy data

ANEMOC3 selected as the reference for the historical period

New regional wave climate projections using *TOMAWAC* and ANEMOC3-Ocean model

Radiative forcing defined by
Climate Change Scenario
SSP5-8.5

7 CMIP6
GCMs
Global Domain

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10m Wind data
(dt=3h)

Spectral Wave Model
TOMAWAC
ANEMOC3-Ocean
domain

Past and
Future Wave
Climate

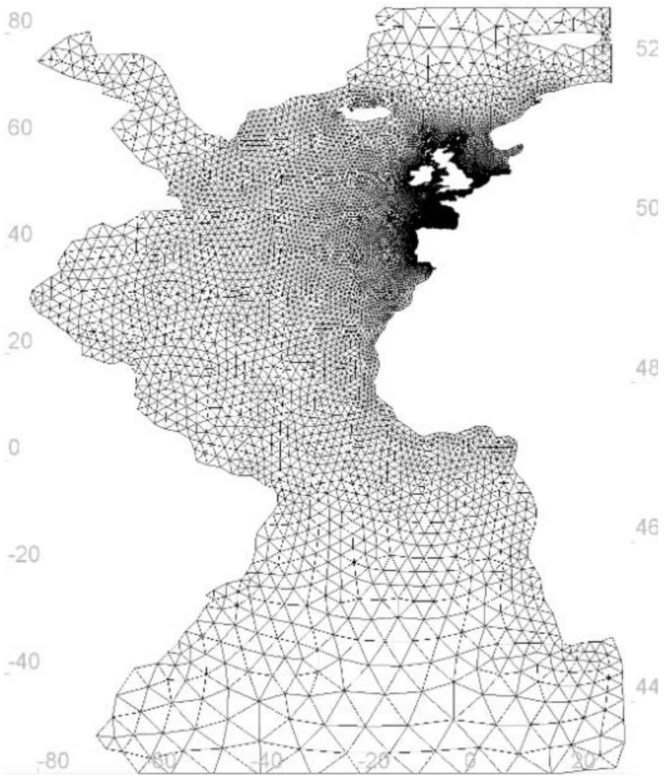

Figure 2. ANEMOC-3 oceanic

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MME statistics with **7 GCMs** for *Meucci et al 2024 (**MME-M**)* and TOMAWAC/GCM (**MME-T**)

ACCESS-CM2
AWI-CM-1-1-MR
CMCC-CM2-SR5
EC-Earth3
IPSL-CM6A-LR
KIOST-ESM
MPI-ESM1-2-LR
MRI-ESM2-0

$\mathrm{H_s}$ mean and percentile for 1985-2014

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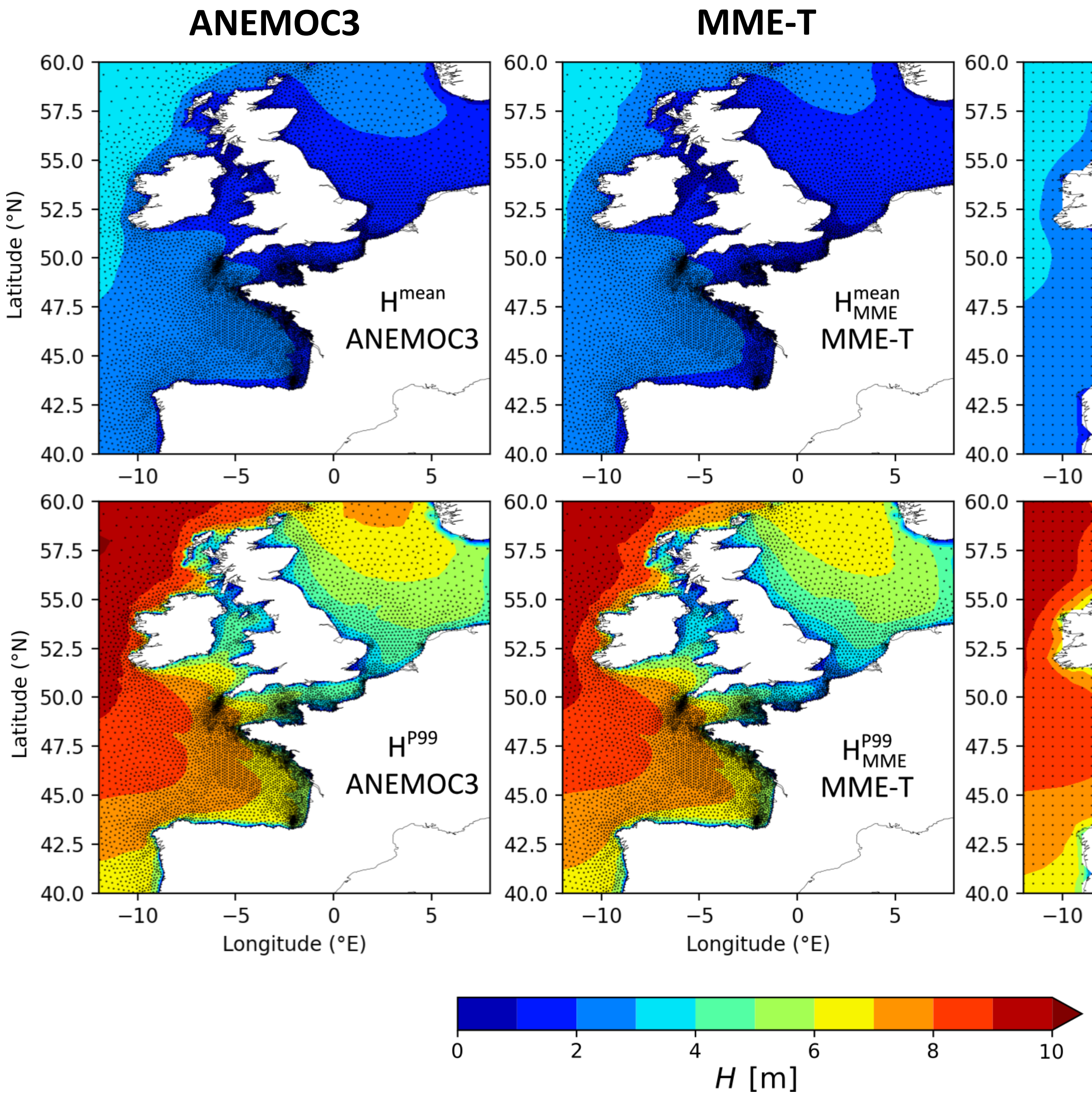
Multi-Model Ensemble (MME)
1985-2014 statistics

$H_s(\boldsymbol{x}, t)$ timeseries for 7 GCMs
Historical Period 1985-2014

Statistics over time $H_s^{stat}(\boldsymbol{x})$ for each dataset for each grid point

$MME\ mean\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)$

Comparison of 1985-2014 H_s statistics



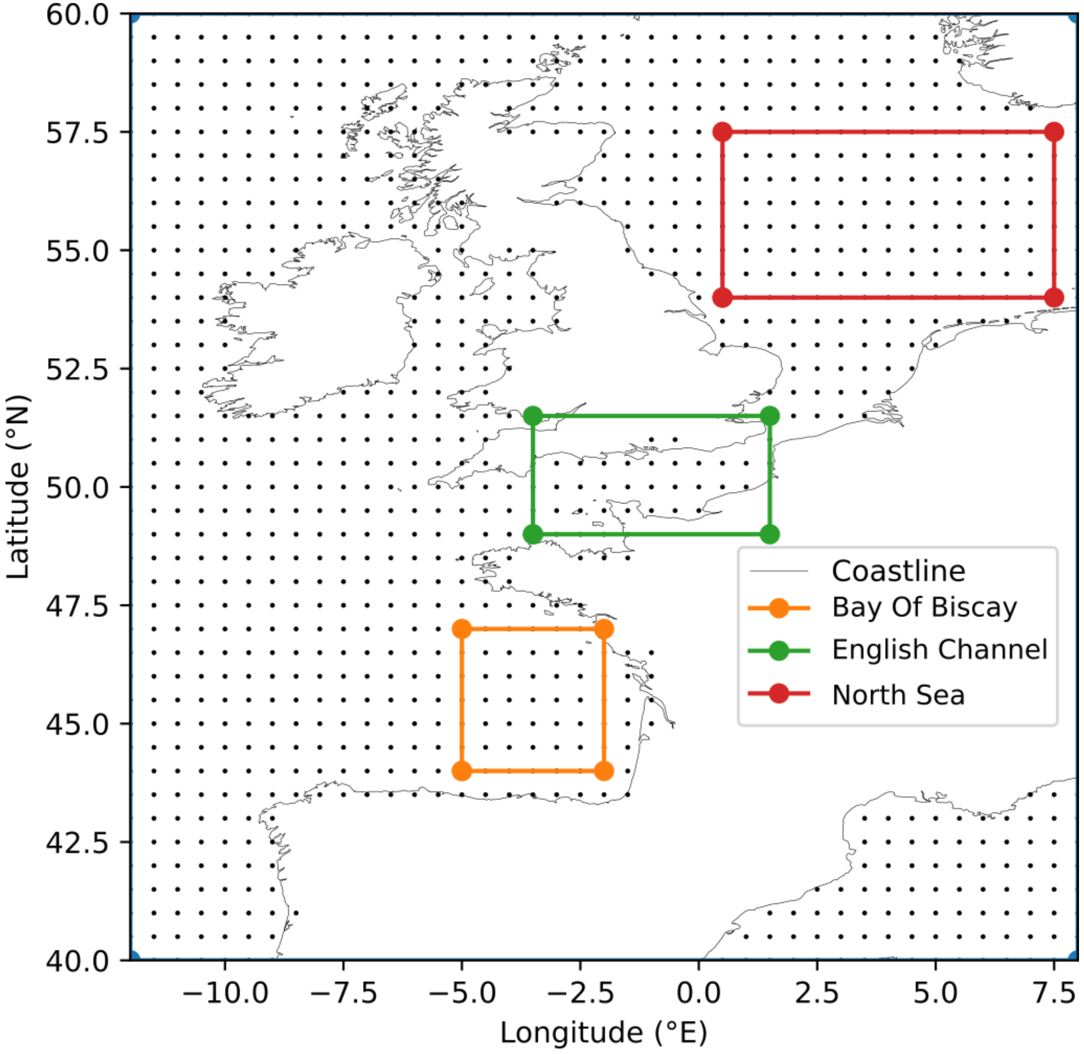
H_s Mean

H_s Percentile 99

⇒ Very good agreement

Reproduction of seasonal climate ?

H_s multi-year monthly statistics averaged in space for 3 regions



<u>Step1: computation of multi-year monthly statistics for each point x</u>

$$H_s^{P99}{}_{January}\,(x) = P99_{1985\_2014}\left(H_s\,(x, \boldsymbol{t} \in \boldsymbol{January})\right)$$

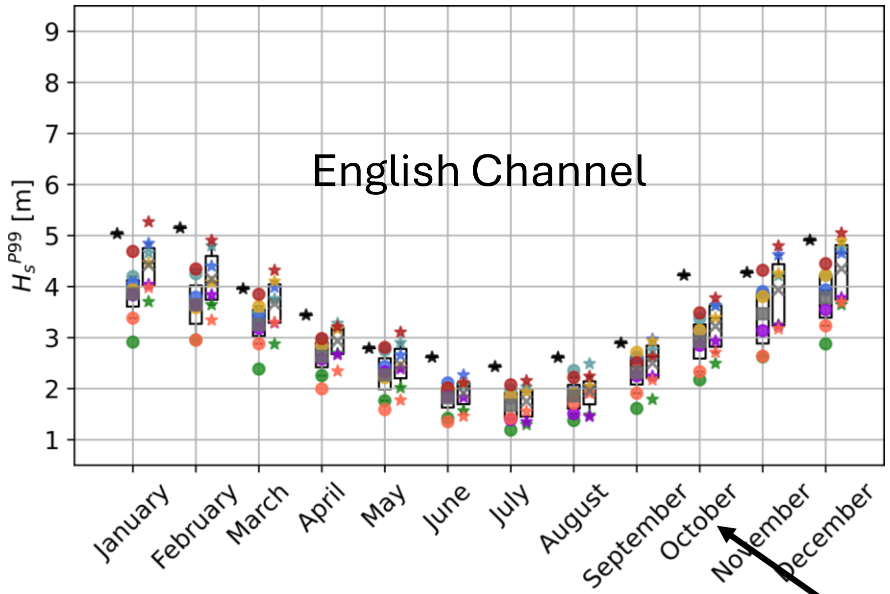
<u>Step2: Spatial mean over regions</u>

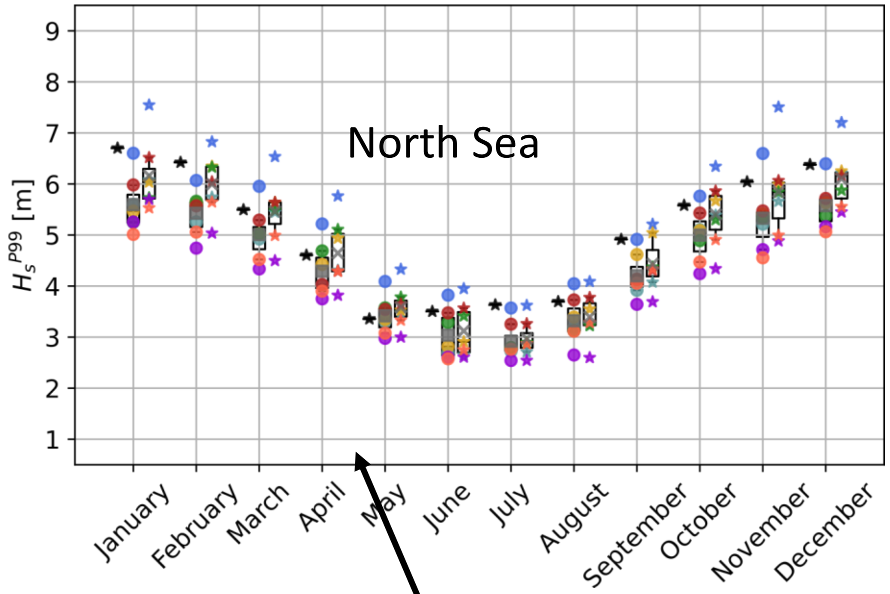
$$H_s^{P99}{}_{January}(region) = \text{Spatial Mean}\left(H_s^{P99}{}_{January}\,(\boldsymbol{x} \in \boldsymbol{region})\right)$$

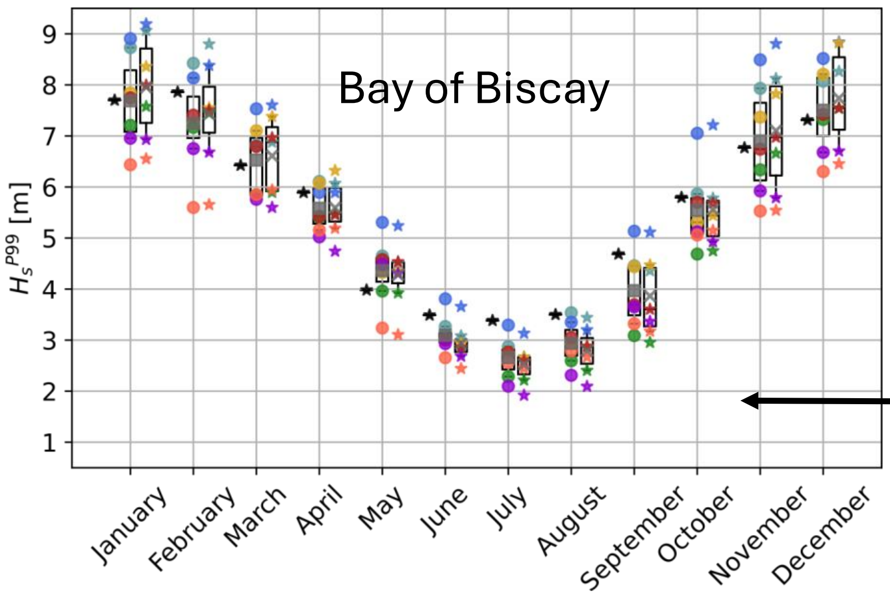
→ **12 points (1 for each month) per region, for each GCM**

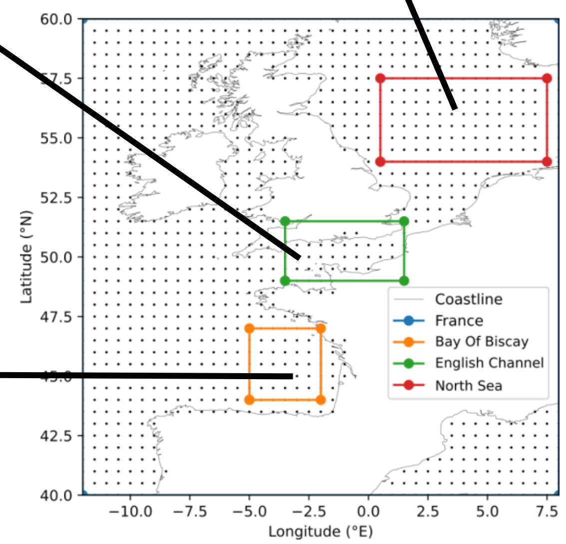
Multi-year montly statistics averaged for 3 regions : H_s P99

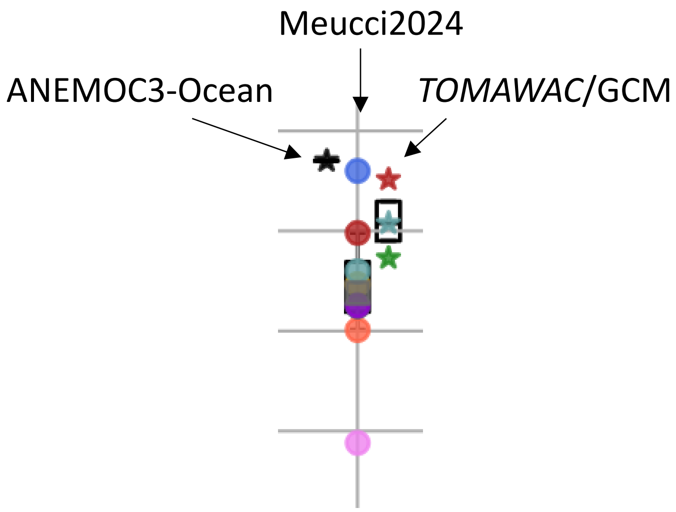
ANEMOC3
MME
MPI-ESM1-2-LR
MRI-ESM2-0
AWI-CM-1-1-MR
CMCC-CM2-SR5
EC-Earth3
IPSL-CM6A-LR
ACCESS-CM2











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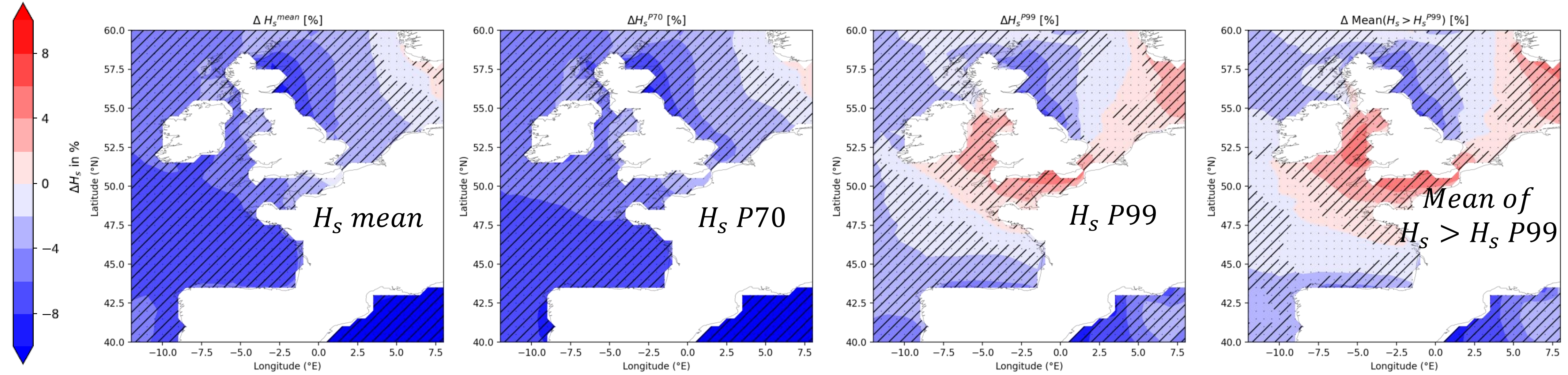
Relative difference of MME statistics

$$\frac{MME\left(H_s^{stat,2071-2100}(\boldsymbol{x})\right) - MME\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)}{MME\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)}$$

$\times$2 for MME-M and MME-T

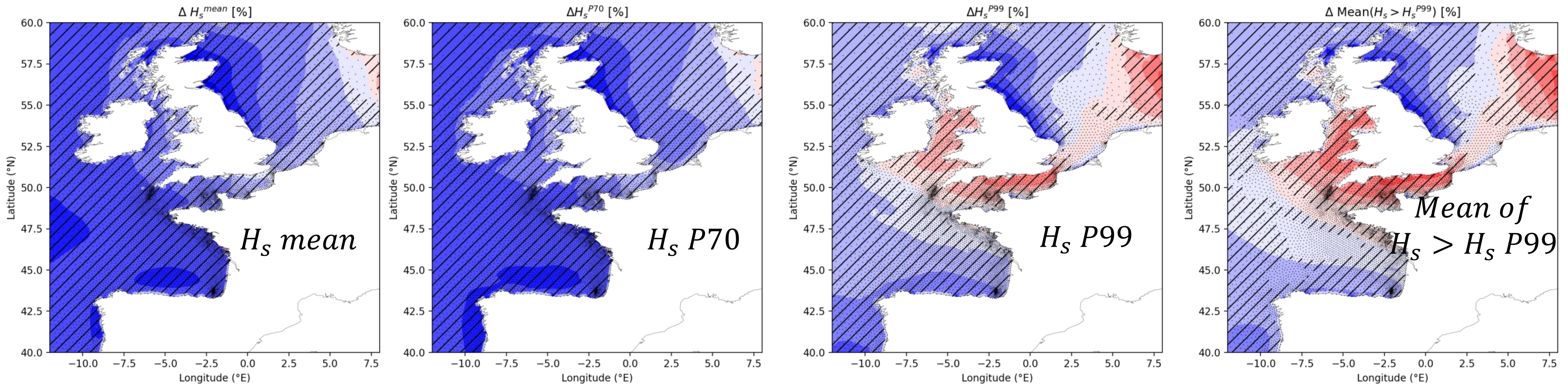
Agreement Level (AG): Number of models whose sign of change is consistent with the evolution of MME statistics.

Hatching if $AG \geq 5$



MME-M (*Meucci 2024*) Relative evolution of 4 characteristic H_s between 1985-2014 and 2071-2100 (**SSP5-8.5**)

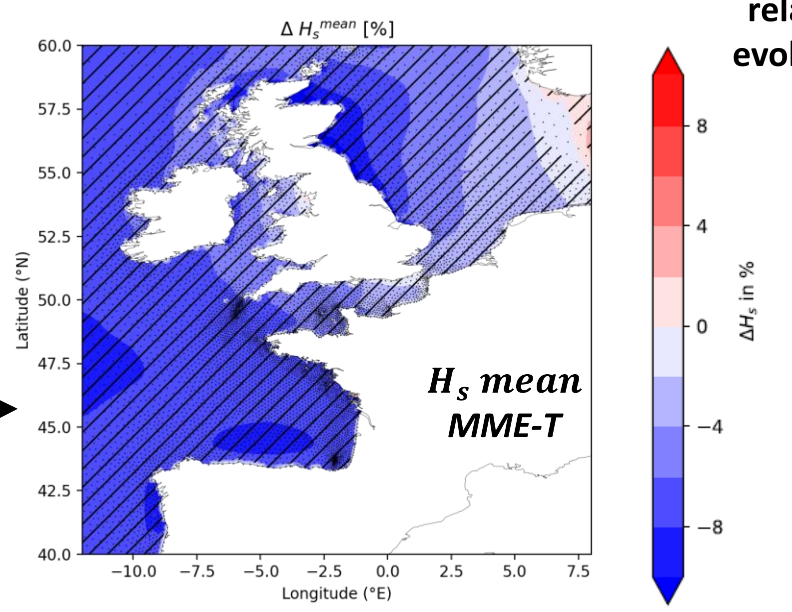
MME-T (*TOMAWAC/GCM*) Relative evolution of 4 characteristic H_s between 1985-2014 and 2071-2100 (**SSP5-8.5**)



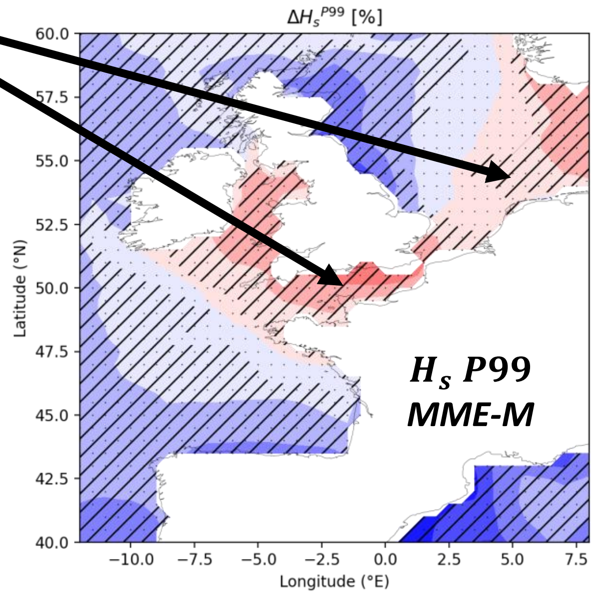
MME relative evolution

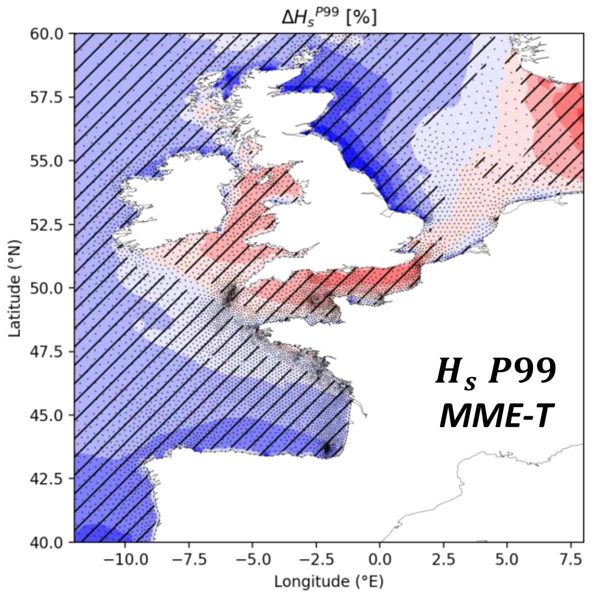
Evolution trends from two 7-GCMs ensembles (SSP5-8.5 scenario):

- **Decrease** in the **mean and low-percentile H_s** accross the entire domain



- **Increase** in the **high-percentile H_s** in the **English Channel** and the **North Sea**





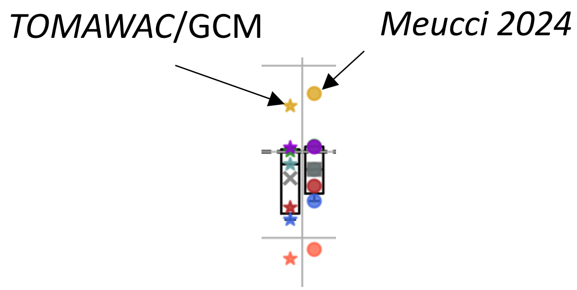
- *TOMAWAC/*GCM and *Meucci2024* provide similar evolution trends

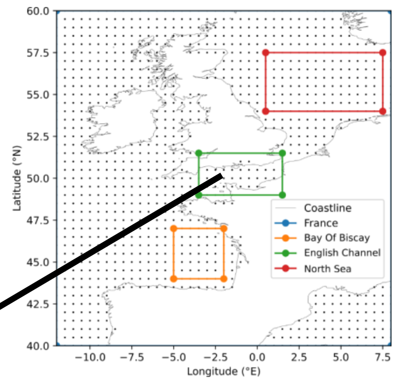
⟶ **Moderate wave model uncertainty**

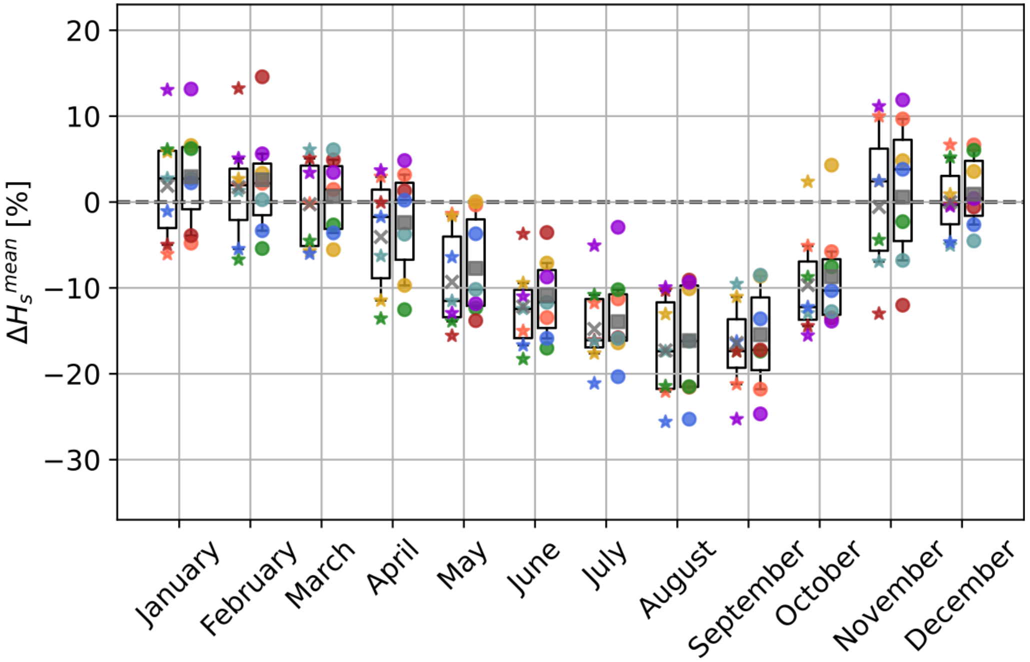
Evolution patterns for each month ?

Relative evolution of monthly statistics English Channel (2071-2100 Vs 1985-2014)

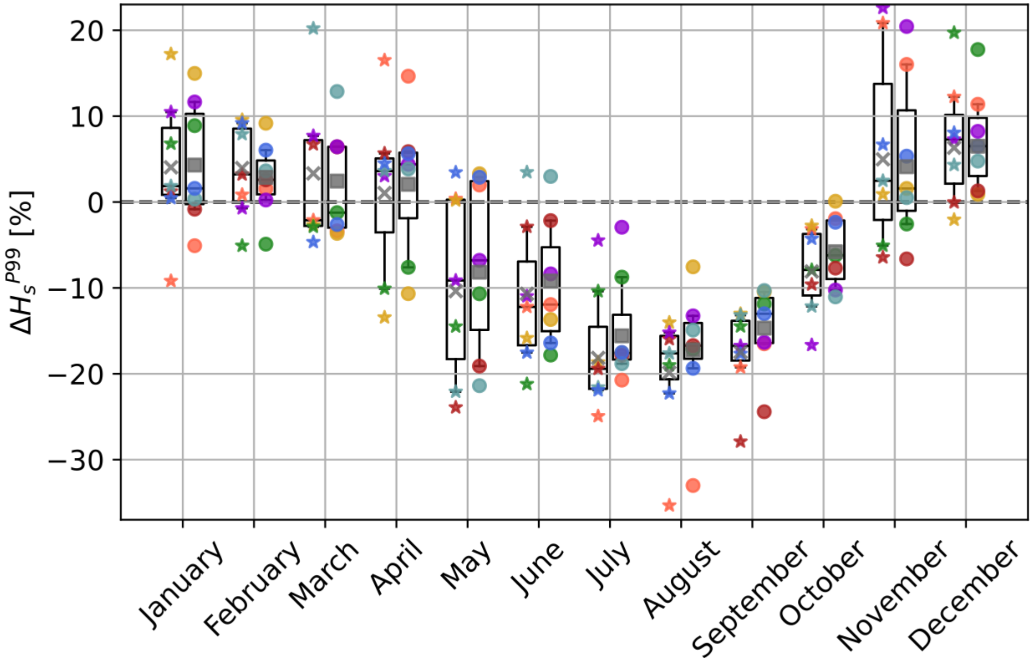
SSP5-8.5







H_s mean



H_s P99

- *MME*
- *MPI-ESM1-2-LR*
- *MRI-ESM2-0*
- *AWI-CM-1-1-MR*
- *CMCC-CM2-SR5*
- *EC-Earth3*
- *IPSL-CM6A-LR*
- *ACCESS-CM2*

⇒ Strong **decrease** in the H_s mean and P99 from **May to October**

⇒ Clear **increase** in the $\boldsymbol{H_s}$ **P99 from November to March**

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Conclusions

- Performance evaluation of the two ensembles relative to the historical reference *ANEMOC3-Ocean* database

- A **global** ensemble and a **regional** ensemble, based on two different wave models and configurations but using the same GCMs wind data, yielded very **similar results and evolution trends**

  ⇒ Performance in enclosed areas is limited by the GCMs wind quality

- ***Meucci et al 2024 + TOMAWAC/GCM projections*** under **SSP5-8.5** scenario indicate:
  - Decrease in the mean H_s accross the entire domain France/Europe (occuring in Summer)
  - Increase in the extreme H_s in the regions English Channel /North Sea (occuring in Winter)

- Similar study carried out for **SSP3-7.0** climate change scenario (not shown here)

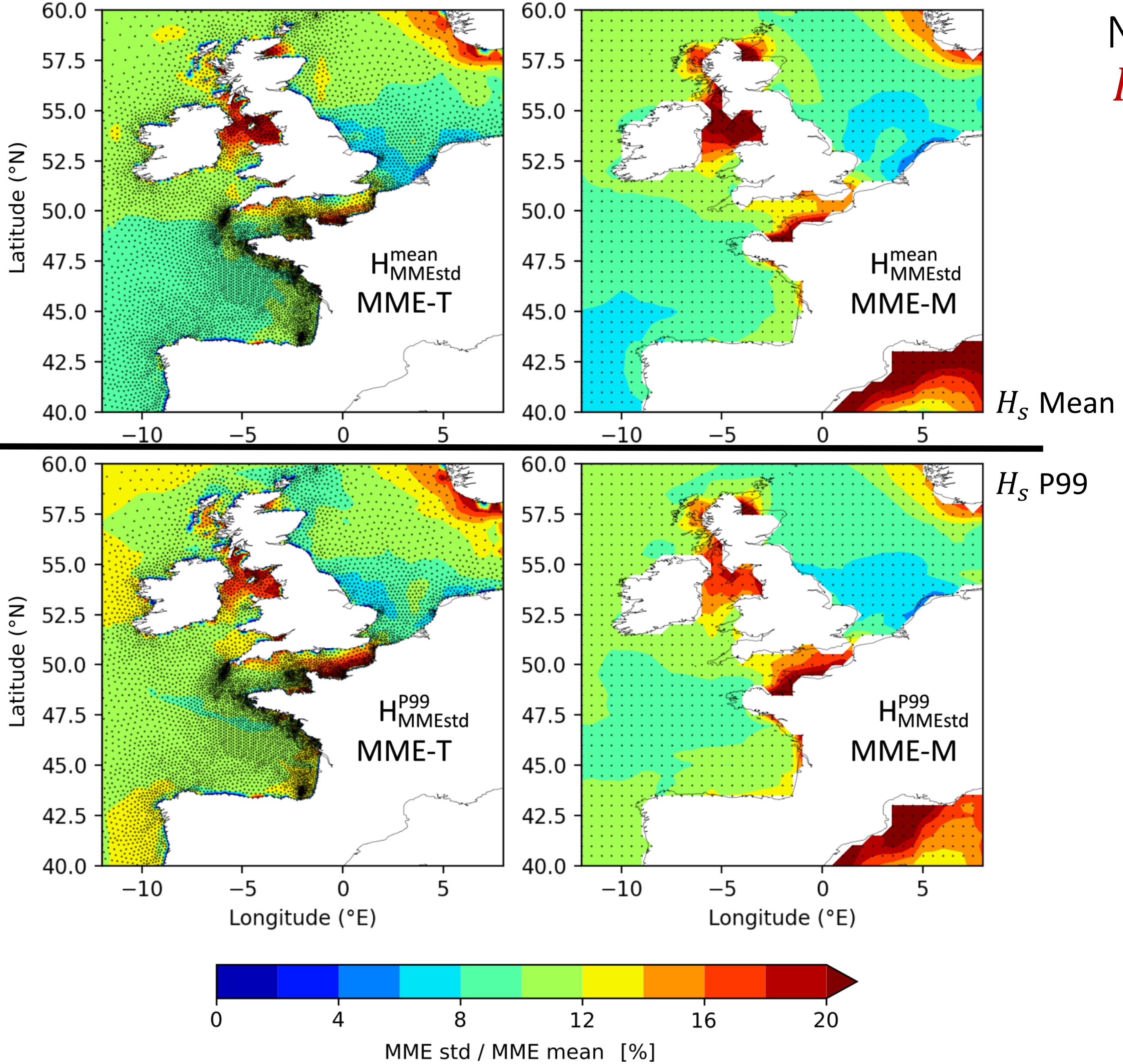
Perspectives

- Comparison of the evolution trends with internal climate variability
- Include additional GCMs
- Coupling with a storm surge model (based on ANEMOC3-Coastal model)

Appendices

Variability from one GCM to another in the historical period ?

Normalized MME standard deviation: H_s Mean et Percentile 99 1985-2014 MME-T Vs MME-M



For each point of the domain :

$H_s^{P99}\ GCM1$
$H_s^{P99}\ GCM2$
...
$H_s^{P99}\ GCM7$

↓

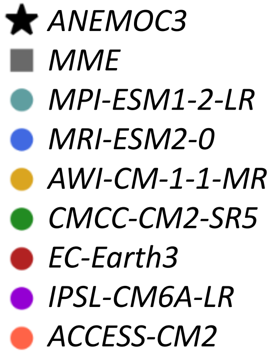
mean MME
AND
std MME

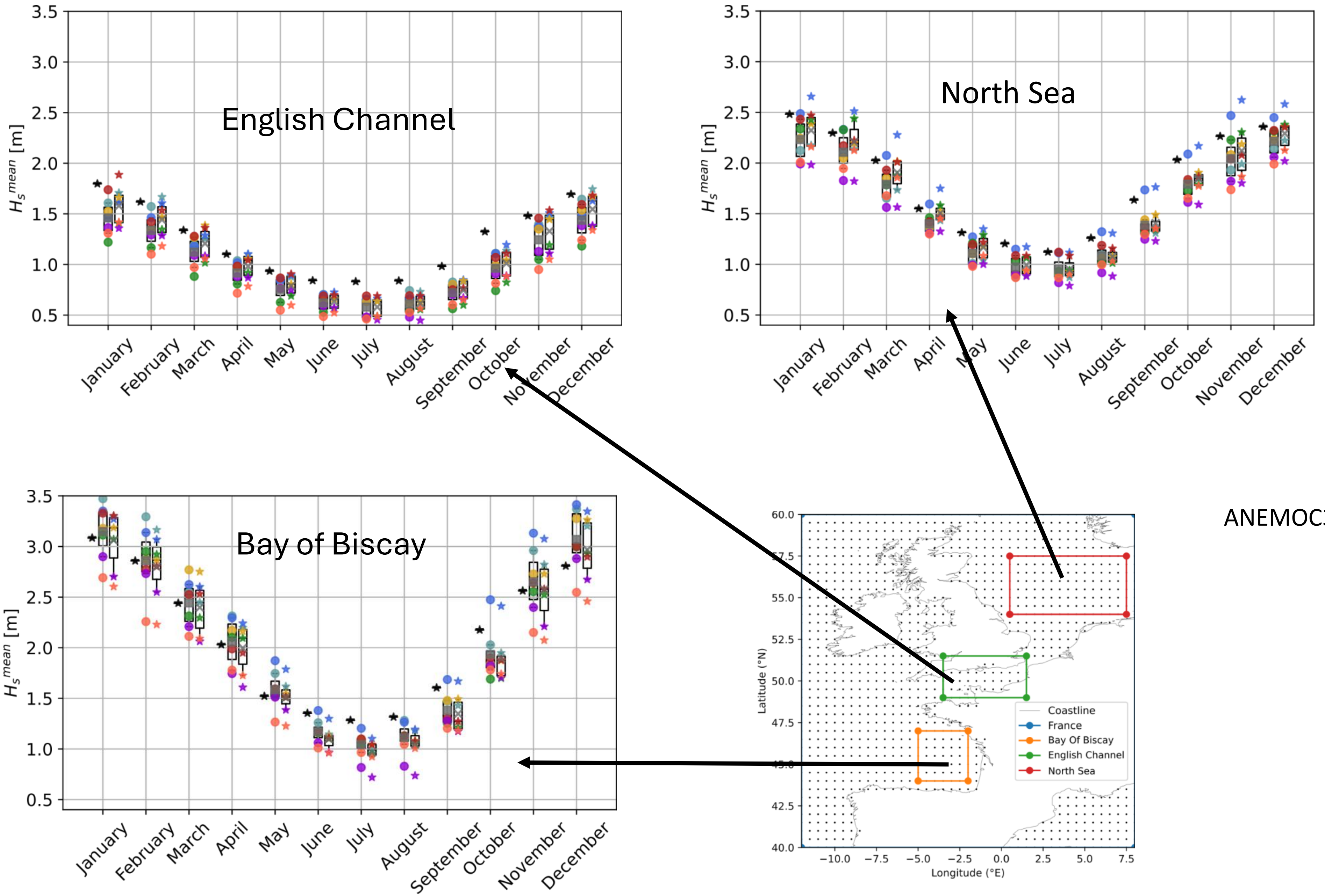
↓

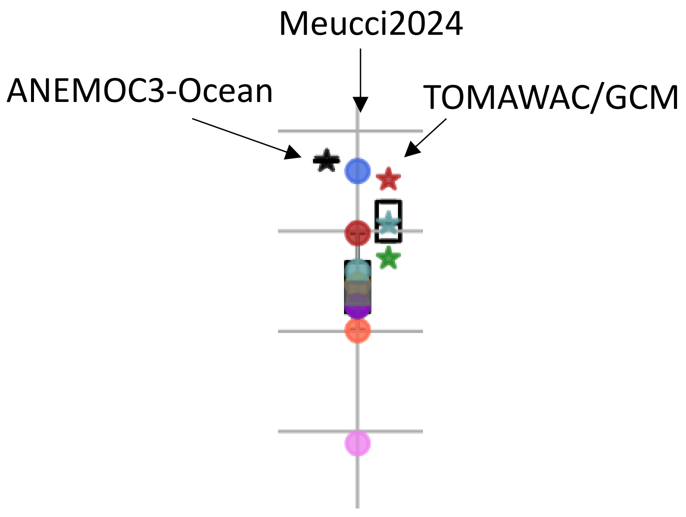
$$\text{Normalized std MME} = \frac{\text{std MME}}{\text{mean MME}}$$

Multi-year monthly H_s Mean (1985-2014)

Multi-year montly statistics averaged for 3 regions : H_s **mean**

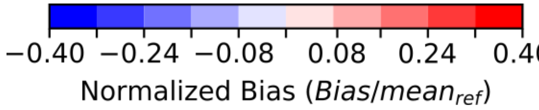


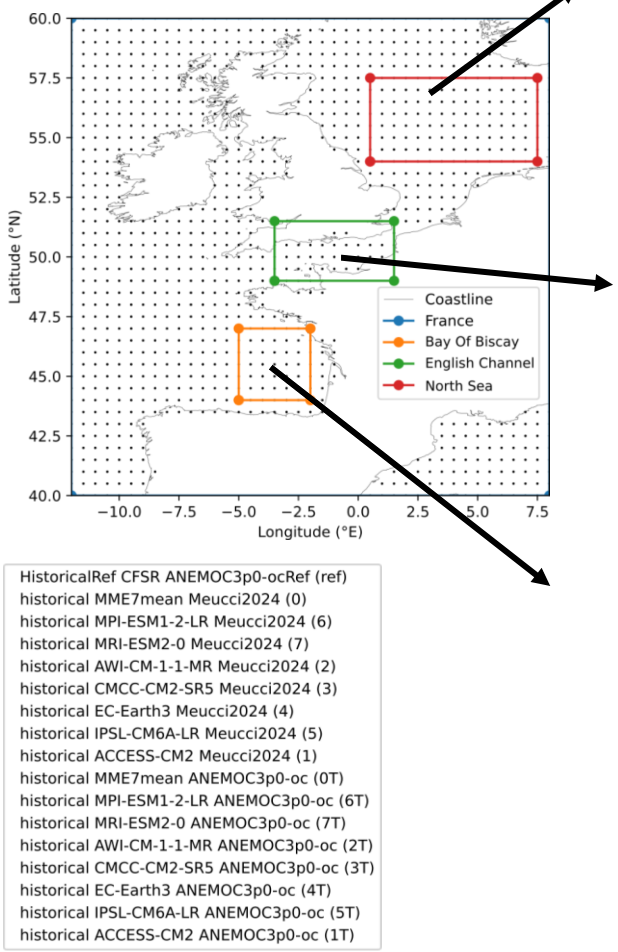




Taylor Diagrams using ANEMOC3-Ocean as Ref (1985-2014)

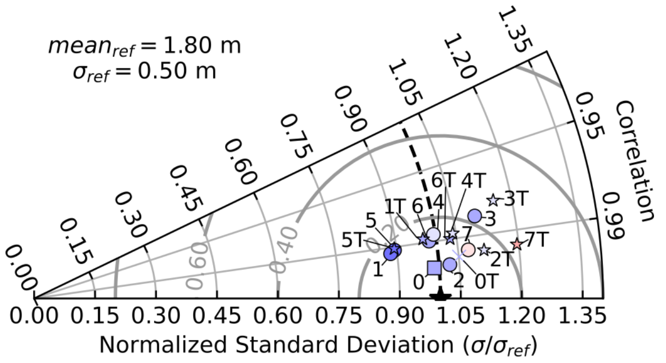
Taylor diagrams of monthly H_s **Mean and P99** averaged for 3 regions (ref: ANEMOC3-Océan)

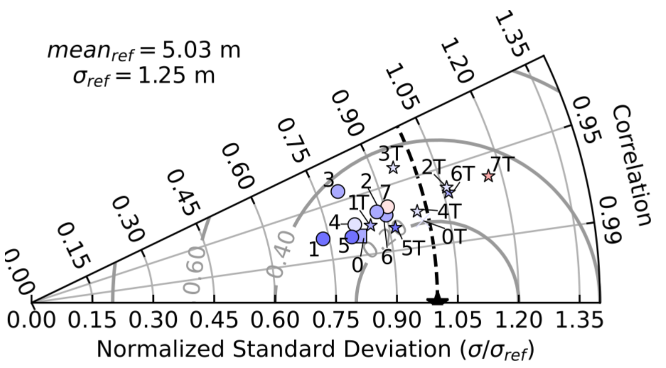




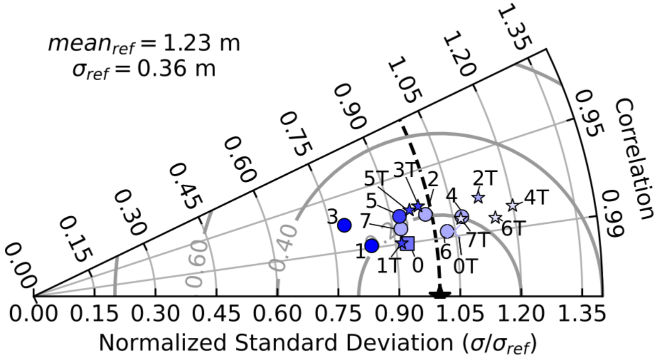
Hs Mean | Hs P99

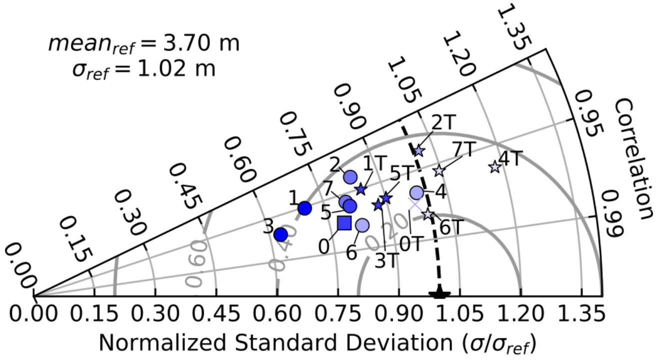
North Sea



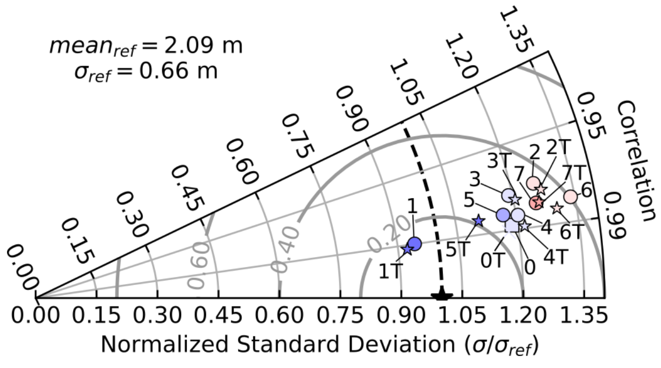


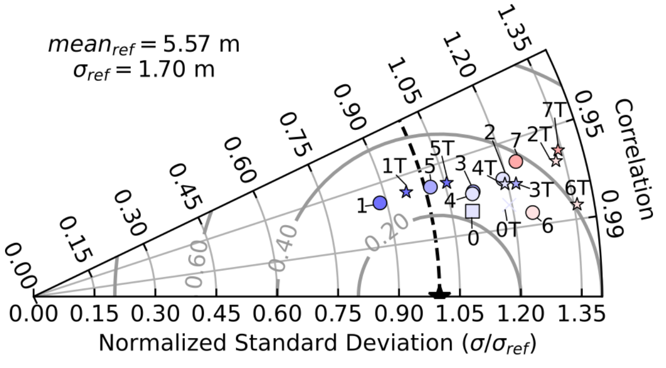
English Channel



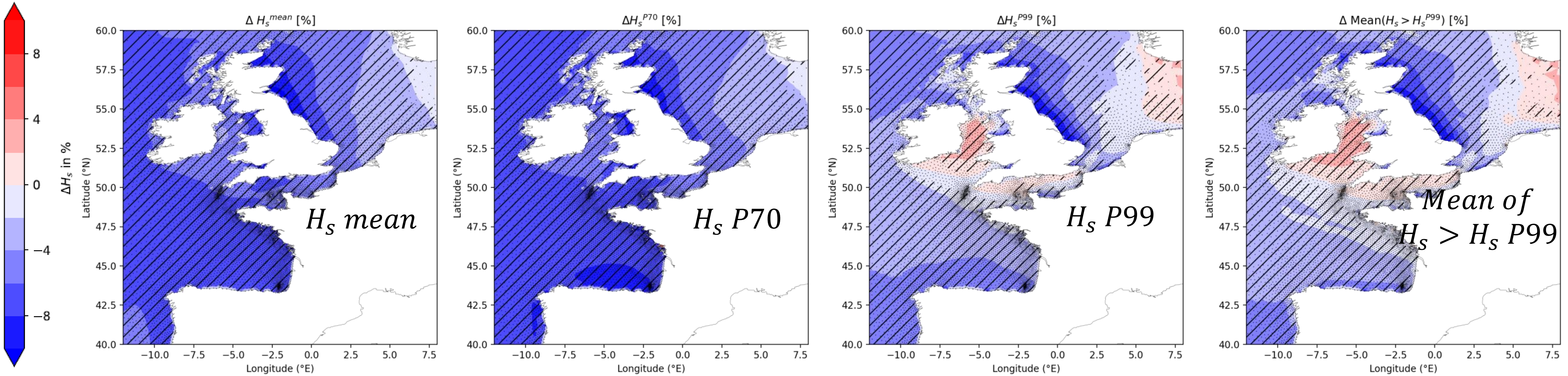


Bay of Biscay



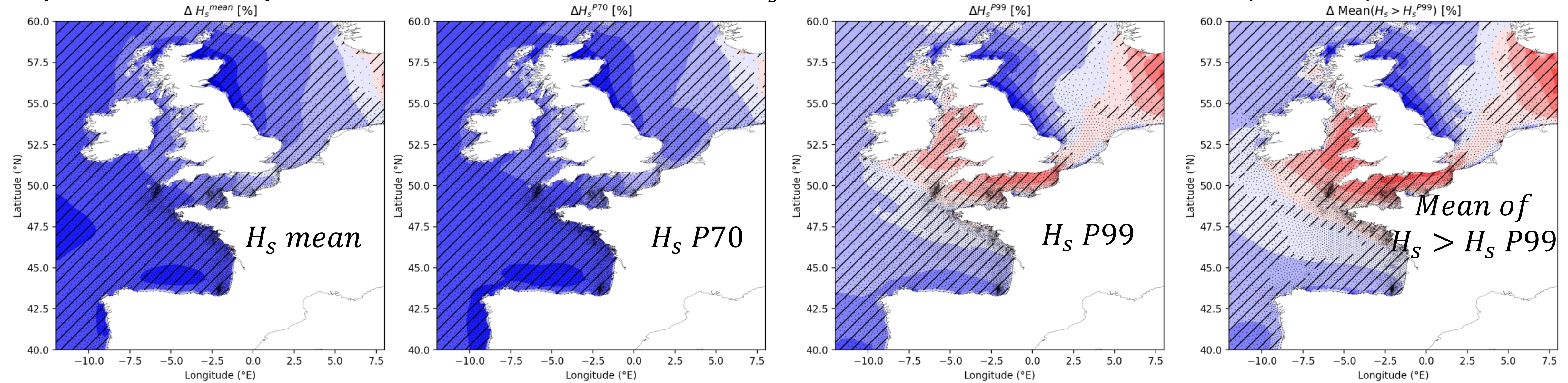


Comparison of MME-T evolutions for SSP585 and SSP370 scenarios



MME-T (*TOMAWAC/GCM*) Relative evolution of 4 characteristic H_s between 1985-2014 and 2071-2100 (**SSP3-7.0**)

MME-T (*TOMAWAC/GCM*) Relative evolution of 4 characteristic H_s between 1985-2014 and 2071-2100 (**SSP5-8.5**)

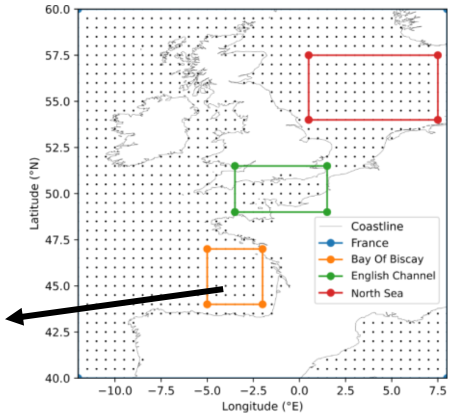


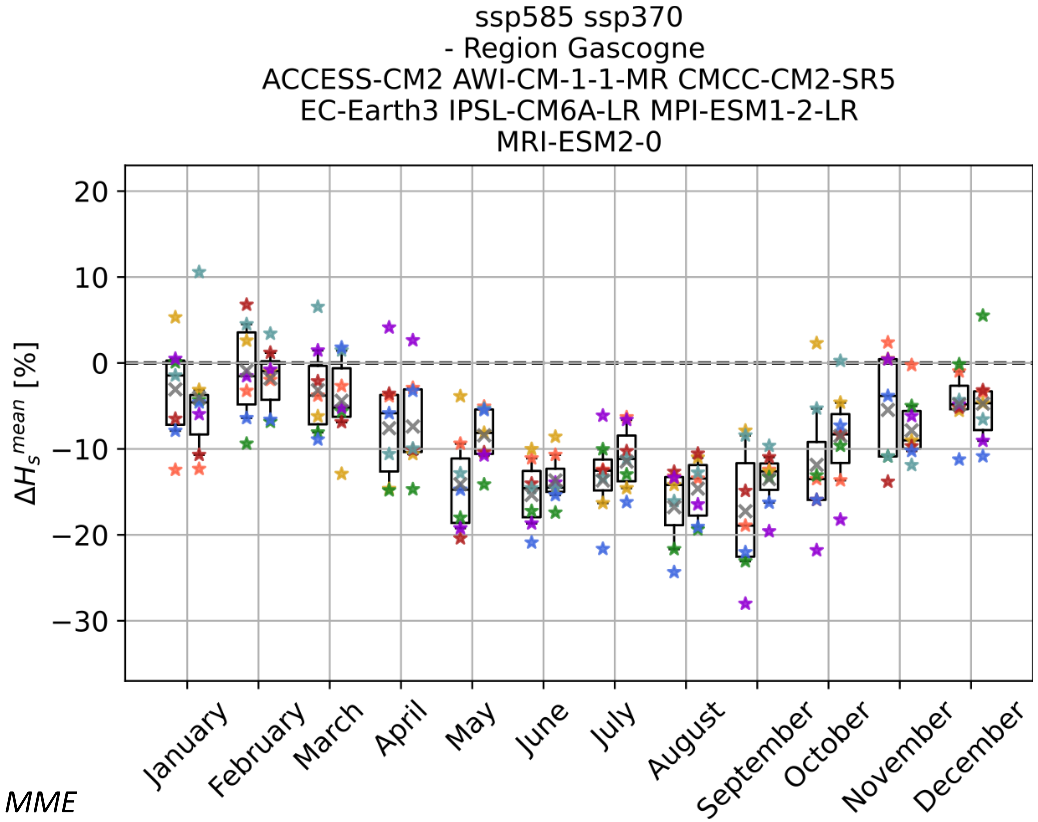
→ Mitigation of the SSP5-8.5 positive trends in SSP3-7.0 scenario

Evolution patterns for each month : SSP3-7.0 scenario

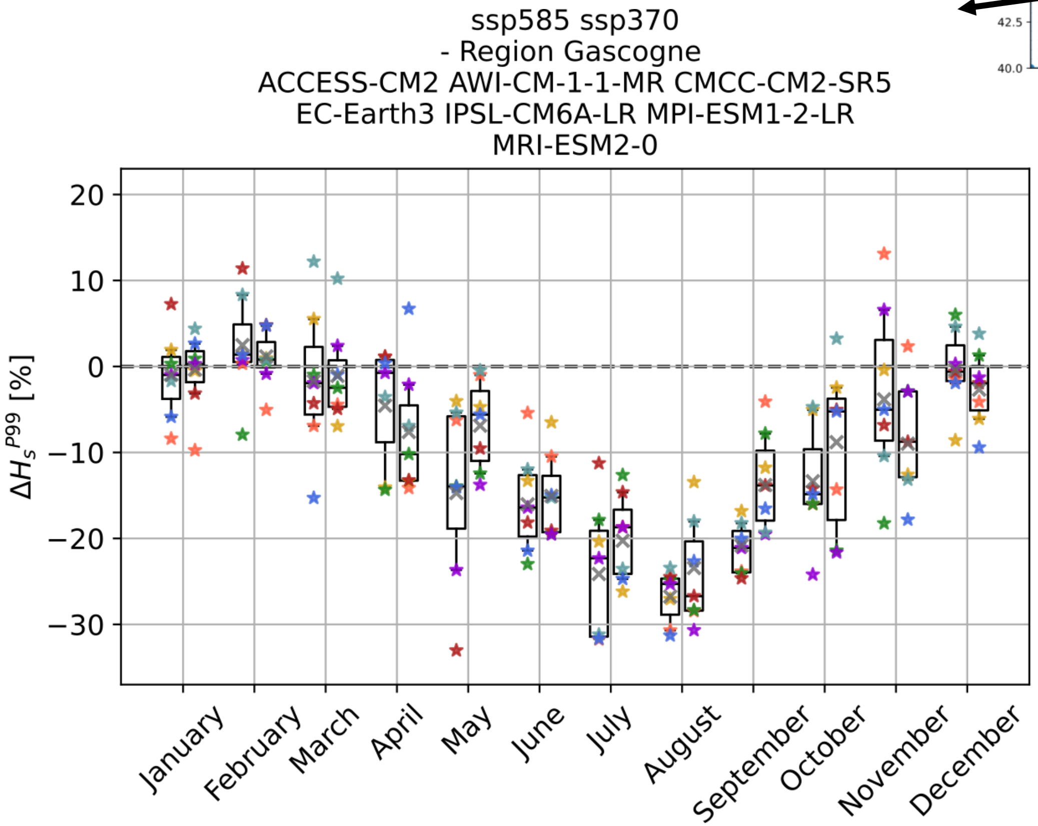
Relative evolution of monthly statistics for the 3 regions (2071-2100 Vs 1985-2014)

TOMAWAC/GCM SSP5-8.5 + SSP3-7.0





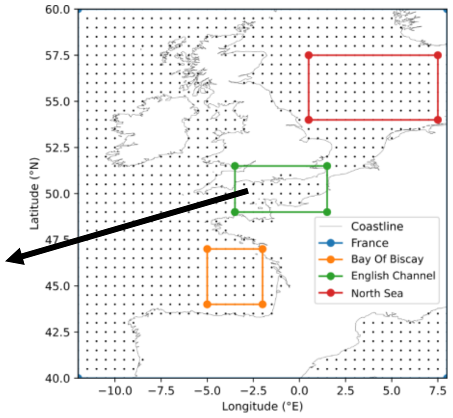
H_s **mean**



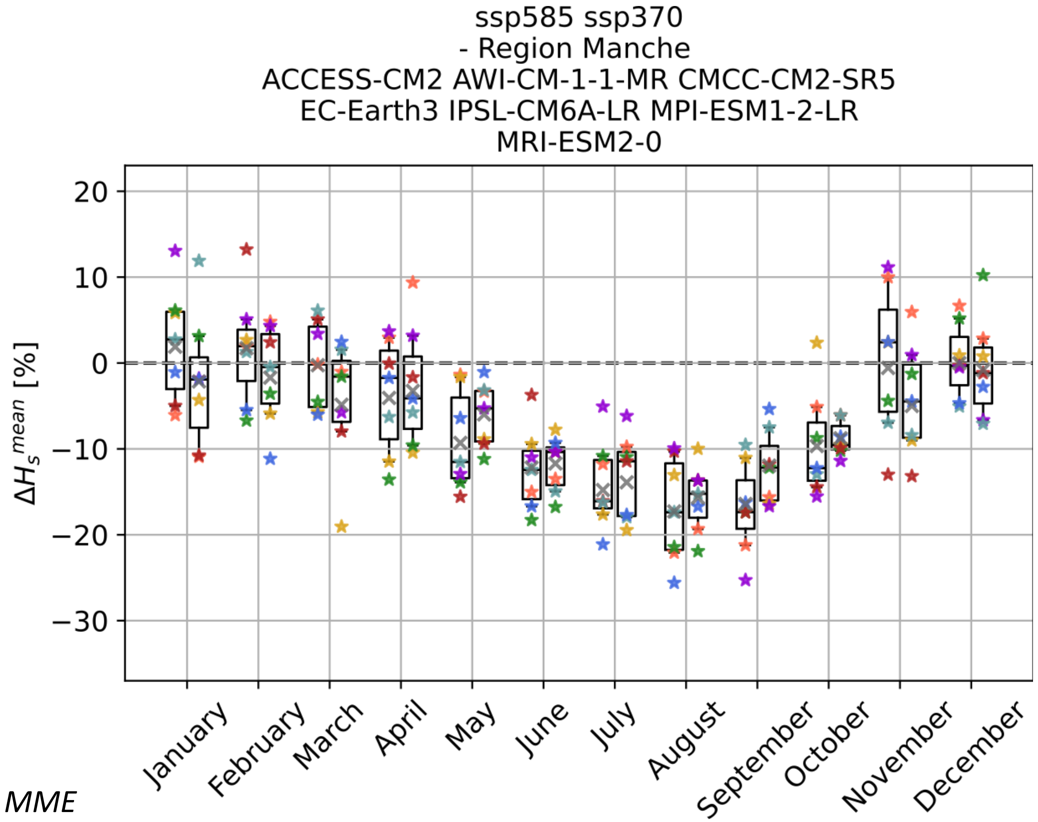
H_s **P99**

MME
MPI-ESM1-2-LR
MRI-ESM2-0
AWI-CM-1-1-MR
CMCC-CM2-SR5
EC-Earth3
IPSL-CM6A-LR
ACCESS-CM2

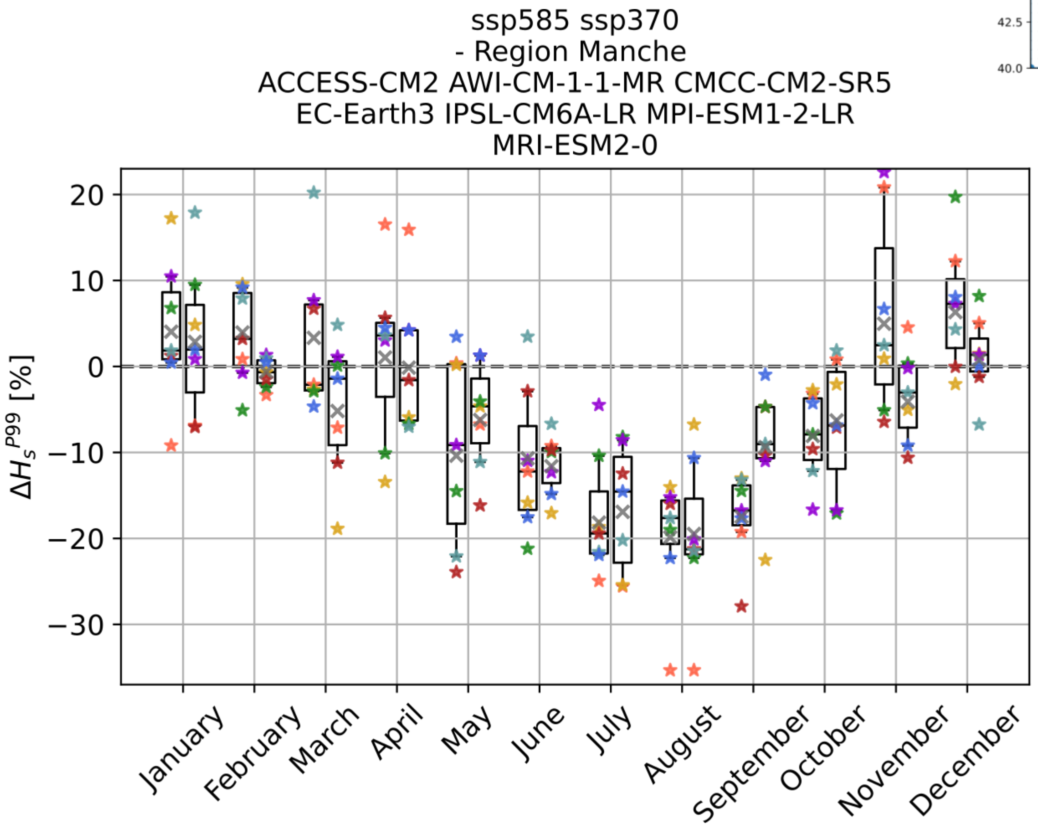
Relative evolution of monthly statistics for the 3 regions (2071-2100 Vs 1985-2014)



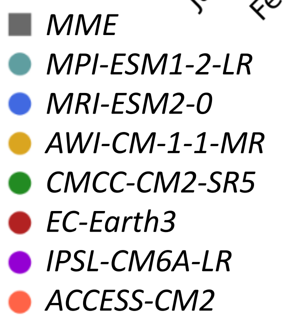
TOMAWAC/GCM SSP5-8.5 + SSP3-7.0



H_s mean

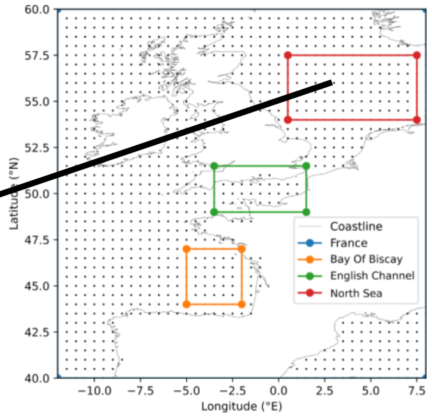


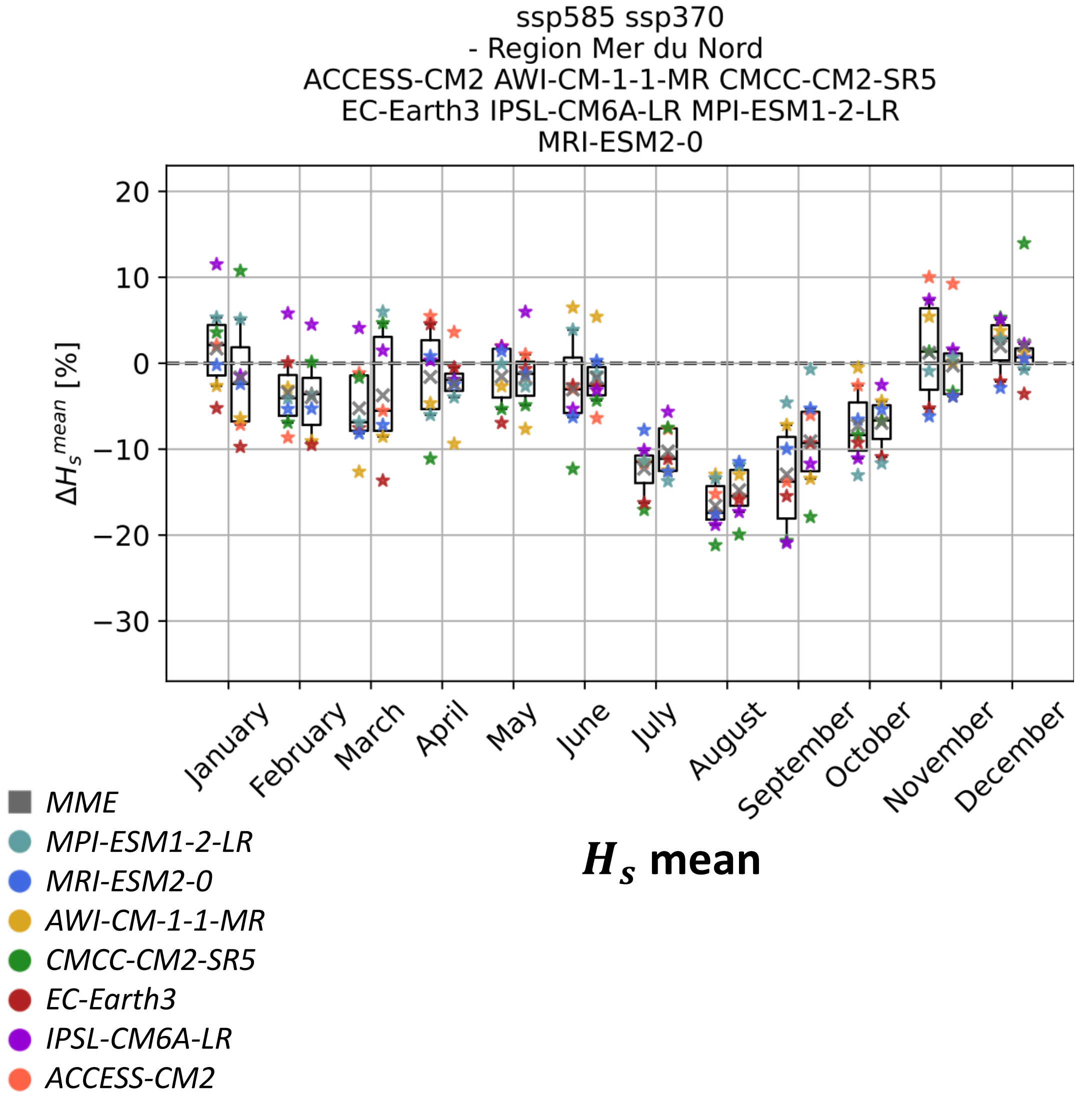
H_s P99



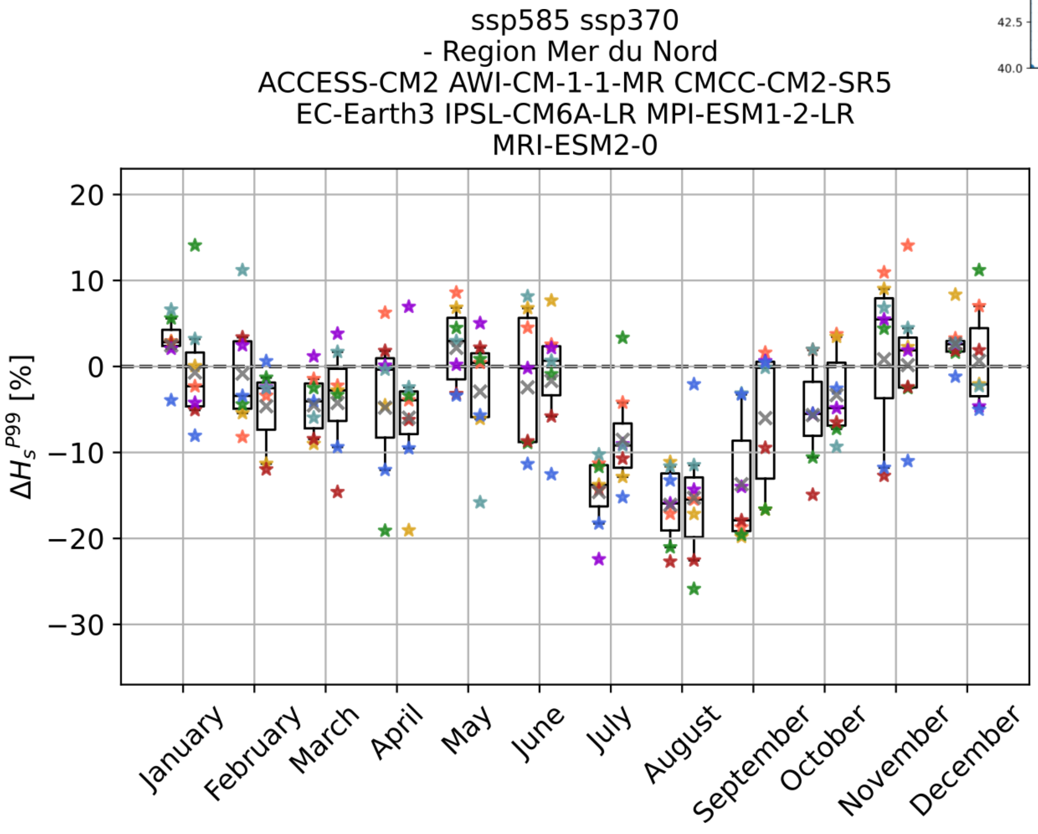
Relative evolution of monthly statistics for the 3 regions (2071-2100 Vs 1985-2014)

***TOMAWAC/GCM* SSP5-8.5 + SSP3-7.0**





H_s mean

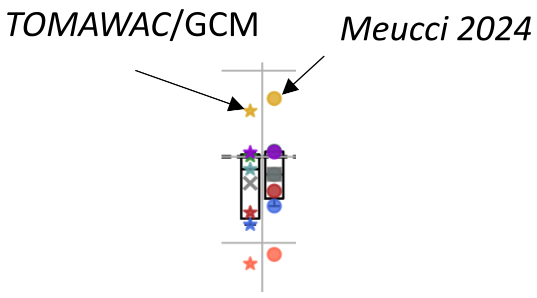


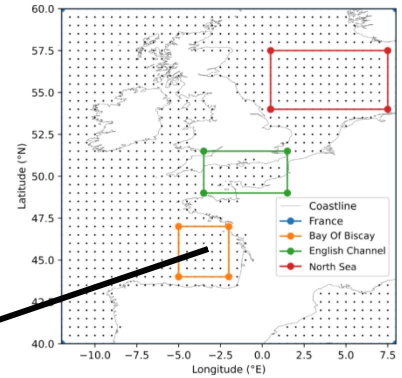
H_s P99

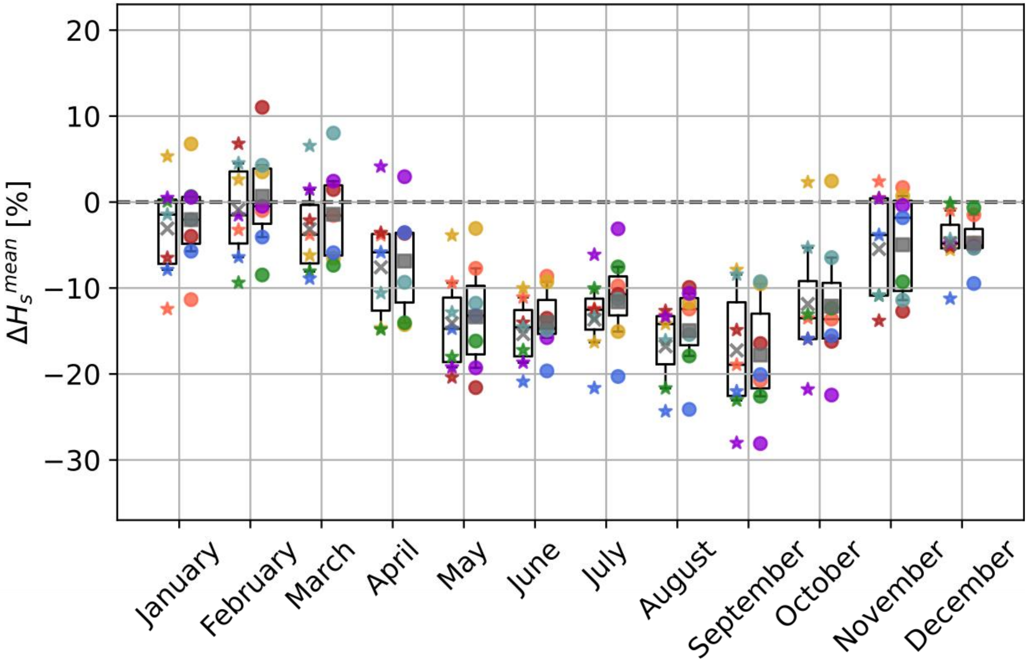
Evolution patterns for each month : SSP5-8.5 scenario

Relative evolution of monthly statistics **Hs Mean and Hs P99**
Bay Of Biscay (2071-2100 Vs 1985-2014)

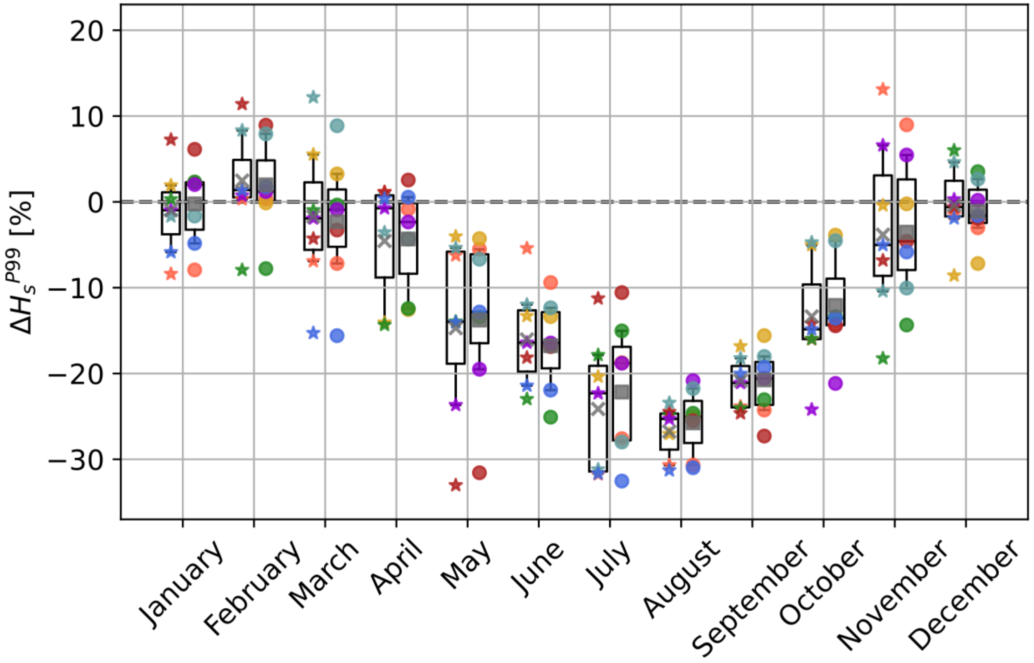
SSP5-8.5







H_s **mean**



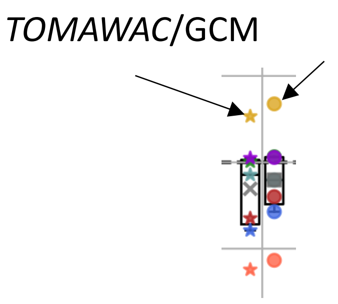
H_s **P99**

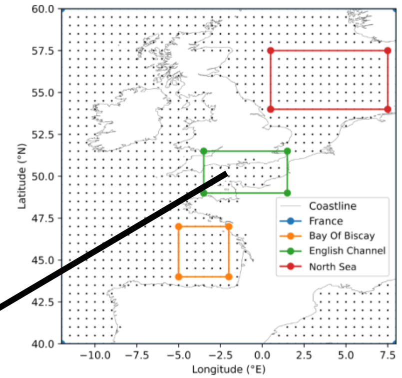
- *MME*
- *MPI-ESM1-2-LR*
- *MRI-ESM2-0*
- *AWI-CM-1-1-MR*
- *CMCC-CM2-SR5*
- *EC-Earth3*
- *IPSL-CM6A-LR*
- *ACCESS-CM2*

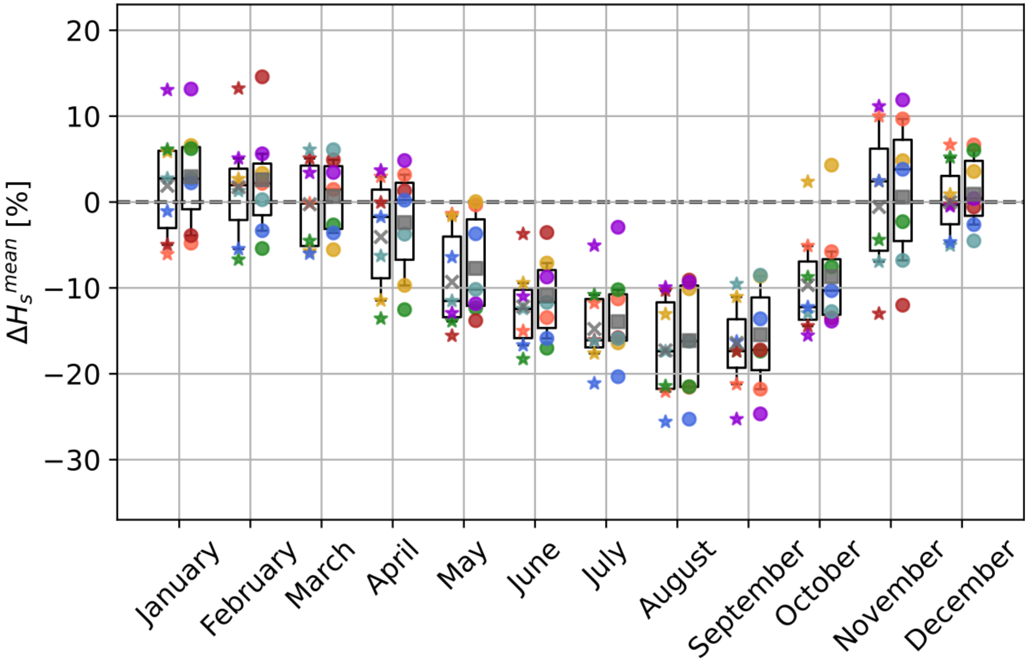
⇒ Strong **decrease** in the H_s mean and P99 from **May to October**
⇒ No clear trend in Winter

Relative evolution of monthly statistics **Hs Mean and Hs P99**
English Channel (2071-2100 Vs 1985-2014)

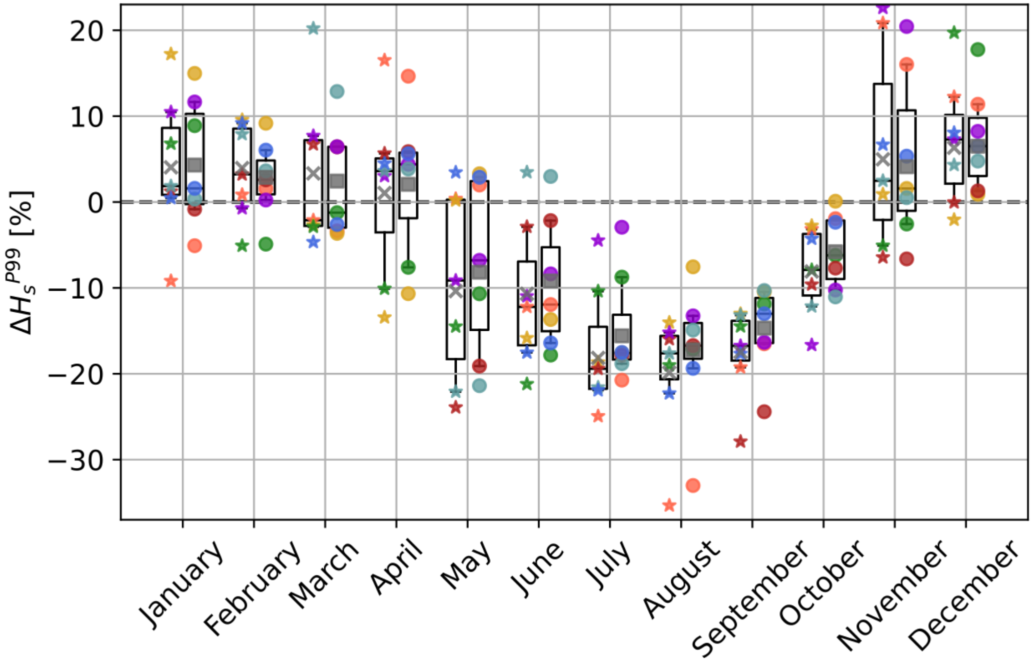
SSP5-8.5







H_s mean



H_s P99

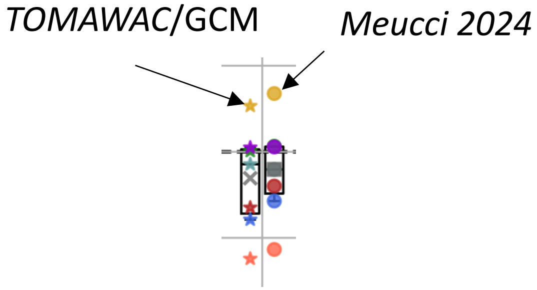
- *MME*
- *MPI-ESM1-2-LR*
- *MRI-ESM2-0*
- *AWI-CM-1-1-MR*
- *CMCC-CM2-SR5*
- *EC-Earth3*
- *IPSL-CM6A-LR*
- *ACCESS-CM2*

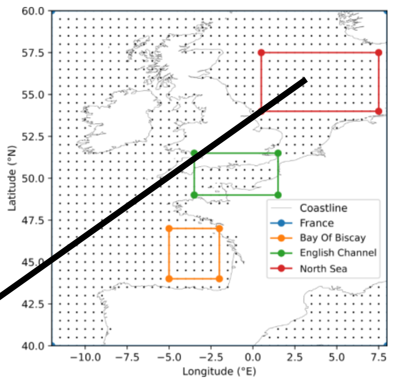
⇒ Strong **decrease** in the H_s mean and P99 from **May to October**

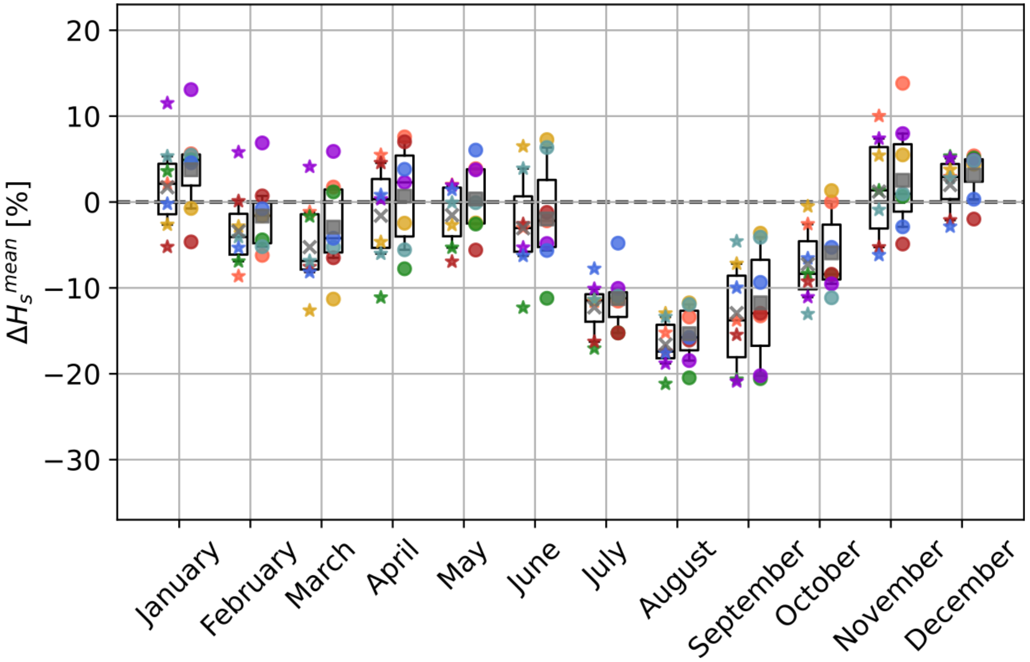
⇒ Clear **increase** in the **H_s P99 from November to March**

Relative evolution of monthly statistics **Hs Mean and Hs P99**
North Sea (2071-2100 Vs 1985-2014)

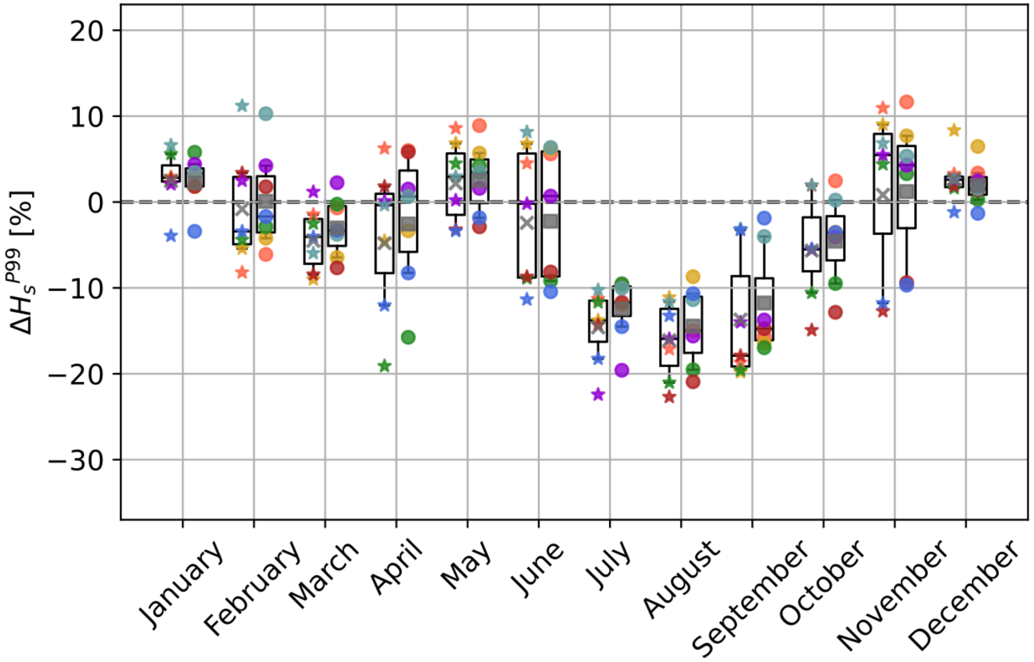
SSP5-8.5







$\boldsymbol{H_s}$ **mean**



$\boldsymbol{H_s}$ **P99**

- *MME*
- *MPI-ESM1-2-LR*
- *MRI-ESM2-0*
- *AWI-CM-1-1-MR*
- *CMCC-CM2-SR5*
- *EC-Earth3*
- *IPSL-CM6A-LR*
- *ACCESS-CM2*

⇒ Strong **decrease** in the H_s mean and P99 from **May to October**

⇒ **Increase** in the $\boldsymbol{H_s}$ **P99 from November to January**

Data analysis details

H_s multi-year monthly statistics averaged in space for 3 regions

Step1: computation of monthly statistics

For each GCM_k, for each point x in the grid:

$$ {H_s^{P99}}_{January,GCM_k}(x) = P99_{1985\_2014}\left(H_{s_{GCM_k}}(x, t \in January)\right) $$

…

$$ {H_s^{P99}}_{December,GCM_k}(x) = P99_{1985\_2014}\left(H_{s_{GCM_k}}(x, t \in December)\right) $$

Step2: Spatial mean over regions

For each region,

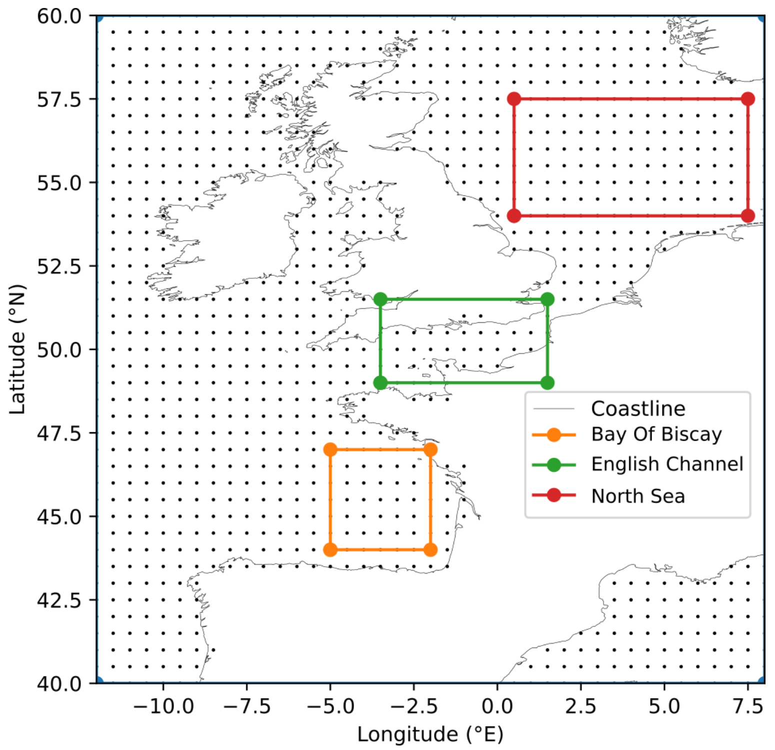
$$ {H_s^{P99}}_{January,GCM_k}(region) = Spatial\ Mean\left({H_s^{P99}}_{January,GCM_k}(x \in region)\right) $$

…

$$ {H_s^{P99}}_{December,GCM_k}(region) = Spatial\ Mean\left({H_s^{P99}}_{December,GCM_k}(x \in region)\right) $$

→ **12 points (1 for each month) per region, for each GCM**

Analysed Regions



Relative difference (SSP585-historical)/historical of *Meucci et al 2024* (***MME-M***) and TOMAWAC/GCM (**MME-T**) MME statistics

ACCESS-CM2
AWI-CM-1-1-MR
CMCC-CM2-SR5
EC-Earth3
IPSL-CM6A-LR
KIOST-ESM
MPI-ESM1-2-LR
MRI-ESM2-0

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

Relative Evolution of **MME** statistics between 1985-2014 and 2071-2100

$H_s(\boldsymbol{x}, t)$ timeseries for 7 GCMs
Historical Period 1985-2014
+
SSP5-8.5 Future Period 2071-2100

Statistics over time
$H_s^{stat,1985-2014}(\boldsymbol{x})$
$H_s^{stat,2071-2100}(\boldsymbol{x})$
for each GCM, for each grid point

$$\frac{MME\left(H_s^{stat,2071-2100}(\boldsymbol{x})\right) - MME\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)}{MME\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)}$$

×2 for MME-M and MME-T

Relative difference (SSP585-historical)/historical of *Meucci et al 2024* (***MME-M***) and TOMAWAC/GCM (**MME-T**) MME statistics

ACCESS-CM2
AWI-CM-1-1-MR
CMCC-CM2-SR5
EC-Earth3
IPSL-CM6A-LR
KIOST-ESM
MPI-ESM1-2-LR
MRI-ESM2-0

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

H_s mean and percentile for 1985-2014 and 2071-2100

Agreement Level (AG): Number of models whose sign of change is consistent with the evolution of MME statistics.

Hatching if $AG \geq 5$

Relative Evolution of **MME** statistics between 1985-2014 and 2071-2100

$H_s(\boldsymbol{x}, t)$ timeseries for 7 GCMs
Historical Period 1985-2014
+
SSP5-8.5 Future Period 2071-2100

Statistics over time
$H_s^{stat,1985-2014}(\boldsymbol{x})$
$H_s^{stat,2071-2100}(\boldsymbol{x})$
for each GCM, for each grid point

$$\frac{MME\left(H_s^{stat,2071-2100}(\boldsymbol{x})\right) - MME\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)}{MME\left(H_s^{stat,1985-2014}(\boldsymbol{x})\right)}$$

×2 for MME-M and MME-T